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DSRC
DEFENSE SCIENCES
RESEARCH COUNCIL

SUMMARY REPORT

DEFENSE SCIENCES RESEARCH COUNCIL SUMMER CONFERENCE

La Jolla, California
July 1997

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Final Report compiled by
Charles Evans & Associates

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SUMMARY REPORT OF THE DEFENSE SCIENCES RESEARCH COUNCIL SUMMER CONFERENCE

La Jolla, California
July 1997

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INTRODUCTION

This report is a summary of the 1997 DARPA-Defense Sciences Research Council Summer Conference held from July 8, through July 31, 1997, in La Jolla, California. The report is submitted to DARPA soon after the conference to allow timely utilization of the results from the conference workshops.

During the year, workshops and program reviews are attended by smaller groups of Council members. These reports are made directly to DARPA and are included in the report submitted at the end of the contract year.

The principal task of the ONR-DARPA Contract is to bring together a group of the country's leading scientists and engineers for an extended period, to permit them to apply their combined talents in studying and reviewing future research areas in defense sciences for the Department of Defense.

The technical direction of the Council is by a Steering Committee comprised of seven representative members of the Council who work with DARPA management to select the relevant topics for the annual Summer Conference, and with the Council membership to develop new areas in defense research. The Council also serves as a resource for other DARPA offices.

The membership of the Steering Committee and the Council varies from year to year in response to the research areas of major interest to the Department of Defense. The 1997 Steering Committee membership is given on the following page and the 1997 Council membership is given on pages v–vii. The DARPA and ONR participants in the 1997 DSRC program are given on page viii.

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July 1997

1997 SUMMER CONFERENCE ACTIVITIES

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
	1	2	3	4 *July 4th Holiday*
7	8	9	10	11
14 *Study:* *Human Performance* *(1 1/2 days)*	15 *Human Performance* DSRC/DARPA Activities *Centcom Briefing and Discussion* *NEW DARPA PMs/DSRC MBRS*	16 *Study:* *UAV* *(1 1/2 days)*	17 *UAV* DSRC/DARPA Activities *Report on Off-Site Wrkshps* *Briefing on DSB CBW Study (tent.)* *New Program Brainstorming (*)*	18 *Workshop: Bioinformatics* *(Formerly:* *New Applied Math)*
21 *Study:* *Multi Functional Dynamic Materials Systems* *(1 1/2 days)* *Steering Committee Mtg.*	22 *Multi Func Dyn Mtrls Sys* DSRC/DARPA Activities *NEW DARPA PMs/DSRC MBRS* *New Program Brainstorming (*)*	23 *Study:* *Applying VLSI* *(1 1/2 days)*	24 *Applying VLSI* DSRC/DARPA Activities *Tutorial* *Steering Committee Mtg.* *(if necessary)*	25 *Study:* *Electronics For Just In Time Weapons Systems* *(1 day)*
28 *Writing Day 1*	29 *Writing Day 2*	30 *Writing Day 3* 1PM-Steering Committee Mtg.	31 *Wrap-Up Day*	

(*)Informal Discussion and Reception to follow

6/20/1997

The agenda for the Summer Conference is prepared initially during the prior year's conference with input from ARPA and the Council. This is refined at subsequent Steering Committee meetings and the workshops are organized. The calendar for the 1997 Summer Conference is shown in the figure above.

TABLE OF CONTENTS

ENHANCING HUMAN PERFORMANCE

G. Kovacs

EXECUTIVE SUMMARY

Objective

The overall goal of this study was to explore three related approaches to enhancing human performance in a DoD relevant context: pharmacological, mesoscopic implants and direct (microscopic) tissue interfaces. The key point about DoD relevance was that, in contrast to most uses of these three modalities as therapeutics, the applications under consideration dealt with applying them to healthy individuals.

DoD Relevance

Enhancing human performance, particularly under adverse conditions, can be of great importance to the DoD. Extension of endurance and strength of humans, mitigation of "jet lag," improvement of sensory and cognitive functions (e.g. motor skills, reaction times, etc.), protection against injury, prevention of performance degradation in low-oxygen settings (a common cause of "pilot error" in general aviation mishaps) and prophylaxis against some forms of chem/bio warfare appear to be achievable using pharmaceutical means. Implantable mesoscopic devices (typically, these are encapsulated electromechanical devices, sometimes with ports to sample bodily fluids) could provide a broad range of functions, including personnel tracking/identification, physiologic monitoring and data storage (the equivalent of a "black box" flight recorder for the body, providing a history of an injury to an arriving medic) and functional augmentation. On a longer time-scale, implantable direct tissue interfaces on a microscopic scale could potentially provide high-resolution connections between electronics and the nervous system for covert communications, direct control of vehicles/exoskeletons, etc.. While all of these technologies would require further development, they could enable a host of DoD relevant performance gains.

Pharmacological and Nutritional Performance Modulators

A wide variety of "non-mainstream" pharmaceutical agents were discussed, including those currently approved for DoD use (e.g. amphetamines) and several that appear to have important performance-enhancing effects but are not FDA approved. Potential compounds were discussed for enhancing strength/endurance and mental acuity, as well as modulation of sleep/wake and diurnal cycles and directing metabolism toward anabolic or catabolic states (the choices of pharmaceuticals used will likely be very mission-specific).

While few, if any, of these compounds have been extensively tested/approved for use in healthy individuals, it appears that straight-forward clinical trials could test their efficacy and safety (however some, such as anabolic steroids, are already known to have serious potential side effects with prolonged use). Anecdotal reports of such non-traditional pharmaceuticals must be regarded with great suspicion. In addition, there may be wide variations in sensitivity to these agents across the potential user base, which would need to be carefully investigated. If FDA approval is necessary, it may be difficult, since these

compounds would need to be proven to provide benefit in the absence of disease (an unusual class for the FDA).

Another interesting issue was that simple nutritional approaches (i.e. choice of foods) can potentially yield useful control over metabolic state through modulation of bodily pH levels, as well as providing sustained energy. This approach could provide a rather broad, albeit low-tech, performance boost. It is likely that very relevant information exists in the sports training area, where work in this area has been carried out diligently for decades.

In addition, consideration was given to the emerging knowledge in the area of animal hibernation (an extremely low-energy state), in which many metabolic modulations of interest occur (reduced energy requirements, resistance to low oxygen states, etc.). An exciting theme that emerged was that through studying hibernation (and the underlying differential expression of common genes), key strategies for metabolic modulation could be discovered and could in turn lead to radically new methods for organ and whole body preservation (the latter in cases of trauma management or long-term space travel, for example). It appears that careful study of differential gene expression in hibernation, coupled with exploration of the gene products provides a first-order roadmap toward increasing our knowledge of hibernation.

Organic drug delivery mechanisms (not necessarily passive) such as gels were considered as a promising means for providing continuous, on/off controllable or even automatically responsive dosing (reacting to needs/events by releasing compounds). The potential for this technology includes the development of external or subcutaneous organic gel drug depots that can operate in any of these three delivery modes. An extremely important point regarding implanted drug delivery methods (both organic and electromechanical) is that the quantities of drugs administered into target tissues or into circulation are much smaller than those needed orally, which is a main reason why implants have the potential to provide useful doses over long periods. By engineering organic polymers to respond to changes in temperature, pH, ionic strength, specific molecules, and other factors (perhaps including external command signals), dosing could potentially be controlled. While these developments would require considerable effort, the benefits should be quite substantial. Applications of this technology could include mission-length dosing of performance enhancers and automatic delivery of CBW antidotes in response to a threat. Key technology limiters for this approach include the need for further development of "reactive" delivery systems, poor correlations between in vitro and in vivo work and between species and individuals, and a lack of FDA-approved materials.

Mesoscopic Implantable Devices

This investigation focused on implants in the mesoscopic size scale ("sugar cube to fist sized") which include current electronic/electromechanical devices such as pacemakers, defibrillators and drug pumps. The use of such implants in healthy DoD personnel appears to be effectively prohibited by current doctrine. However, exploration of this area seemed fruitful since on a case-by-case, cost-benefit basis, such implants may prove to be acceptable where no better alternatives exist.

Continuing with the theme of drug delivery, current and future implantable electromechanical drug pump systems were considered. At present, "hockey-puck sized" implantable drug pumps exist that can provide programmed dosing over long periods

(months to years) with the capability to be refilled as needed through the skin. In contrast to these relatively large devices, miniaturized electromechanical and purely fluidic devices may provide next-generation alternatives, with major reductions in volume and cost. For any of these implantable drug pump approaches, a key issue is that while micromachining and other miniaturization technologies can considerably shrink pump volumes, poor volumetric scaling of pharmaceuticals (i.e. how concentrated solutions can be made before precipitation or other effects render them ineffective) and power sources may be critical limiters. Important advances could be made in the area of implantable drug pumps if sensors could be developed that could operate without drift of failure in the body, thus allowing full closed-loop dosing to be implemented. In addition, advances in fluidics, particularly at the microscopic scale, would enable the precision delivery of pharmaceuticals, such as hormones, that are only required in very small doses.

Beyond existing commercial implants, their appear to be three key areas for application of mesoscopic implants: identification/location of personnel, physiologic monitoring and direct modulation of physiologic state (or other enhancements). While it can be argued that one should not implant anything into healthy personnel, there are several compelling reasons to consider it, including the fact that the environment for sensing physiologic parameters is far richer subcutaneously than externally. The key factors in implementing devices in any of the three categories mentioned above appear to be keeping the devices relatively simple in function (at first) and small in size (allowing for minimally invasive implantation) and initially focusing on sensing functions.

Overall, most of the technologies for implementing such devices exist in the commercial sector, yet key limiters remain, including power source density (batteries still form the vast majority of the physical volume of implants and limit their functional lifetimes), a relative lack of sensors that are directly compatible with tissue fluids, reliable microfluidic devices, and materials. Example DoD-relevant implantable devices might include monitors of core body temperature or gaseous nitrogen formation in blood (the bends) for diving operations; a combat "black box" monitor to measure, store and analyze physiologic state to provide vital feedback to the individual (e.g. state of hydration) and to keep a record of physiologic events in case of injury; programmable (or manually-activated) pharmaceutical delivery devices for CBW countermeasures; and many others. The simplest and most immediate applications appear to be those in which the human body is monitored, or even used as a sensor.

Direct (Microscopic) Tissue Interfaces

The "highest resolution" interface to tissues such as the nervous system can be obtained using microscopic arrays of electrodes, potentially capable of communicating with individual neurons. While clearly farther in the future than the other two categories of performance enhancers considered, direct neural interfaces offer the potential of highly parallel input/output channels between electronics/sensors and the human nervous system. In the future, such interfaces could conceivably be used to provide extra, or augmented, sensory channels, covert communications, direct storage/recovery of information, etc.. Impressive results have been achieved in higher animals, such as the use of recordings from motor cortex to make reasonably accurate predictions of movements *before* a monkey made them. It is clear, however, that this sort of application in humans is decades off.

Such interfaces are, under NIH funding, being developed as prosthetic devices for handicapped patients (e.g. interfaces for replacement of auditory, visual and motor functions). These technologies have been, and probably will be, in development for many more years before being practically applied in those settings, let alone in healthy individuals. There was a general consensus that it did not make any sense to attempt implants such as probes into the brain in DoD personnel until the technologies were solidly proven in patients for whom their roles were restorative rather than augmentative.

It appears that the engineering of the neural probes themselves is quite mature and not a primary limiter of their use. However, materials, packaging, telemetry and lack of understanding of interface physiology appear to be critical issues needing more attention. Despite the 25+ year development of the neural interfaces currently in research use, it seems that only in the next few years will researchers in this field finally approach a realistic feasibility demonstration in humans. Only at that point does further development and ultimately consideration of use in healthy humans merit much consideration.

Discussion

It appears that for the pharmacological enhancement area, there is potential for several near-term "wins." While clinical studies may be outside of DARPA's current operational envelope, the potential performance gains available may merit consideration nonetheless. Carefully-designed, large-population, blinded clinical trials in typical DoD populations are clearly required to clearly assess the efficacies, interactions, contraindications and potential physiologic "payback" costs of potential performance enhancers.

In terms of drug delivery systems, it appears that organic delivery means could provide extremely relevant results if the technologies for modulatable or completely automatic ("reactive") dosing could be further advanced. This could provide many advantages over conventional (manual) dosing. Mesoscopic drug delivery systems also appear to have some merit, but only the smaller-sized devices (beyond the current, FDA-approved commercial state-of-the-art) appear realistic for DoD use in humans due to their more acceptable size. These electromechanical or purely fluidic delivery systems could not entirely be replaced by organic delivery systems because some pharmaceutical agents may not be compatible with the latter (for example, unstable compounds could be stored as two stable precursors in an electromechanical implant, reacted and dispensed by a pump as needed). If suitable sensors could be developed, drug delivery could be done in a closed-loop fashion, providing unprecedented capabilities.

Other applications of mesoscopic implants that could have significant DoD impact include compact, sensor-based devices to access the information-rich subcutaneous environment. Potential devices include physiologic monitors and sensor-based systems used to warn of impending problems (e.g. decompression sickness, core body temperature depression, dehydration, etc.) potentially via transmission of a signal to an externally worn device such as a wristwatch (it should also be noted that piezoelectric "beepers" are known to be audible to individuals through their flesh). It is important to observe commercial technology developments in this area, since many of the enabling technologies for the implants are already available in that sector. However, solutions to the problems of providing adequate implantable power (e.g. with rechargeable "supercapacitors," biological energy sources, or other technologies) and developing improved implant materials (e.g. blood compatible) would have broad impact for all types of electronic implants. For

electromechanical drug delivery systems and physiologic monitors involving body fluid contact or sampling, improved sensors and fluidic components will also be required to survive in physiologic environments.

On the microscopic scale, direct interfaces to the nervous system appear to be one or more decades from any realistic application that could directly benefit the DoD (with the exception of rehabilitation). The engineering of the probes and circuitry appears quite mature, but major hurdles still exist in the areas of materials, packaging, power and our underlying knowledge of the physiologic connection between neurons and the interfaces. Key researchers in this field insist that they are only a few years from proof-of-concept demonstration in humans, which would pave the way for implants in handicapped individuals (which is a necessary prerequisite for implants in healthy DoD personnel). This type of implant seemed to be the least obviously useful as a performance enhancer for DoD applications in humans, but in the short term may be important for interfacing to the nervous systems of animals.

In summary, it seems clear that there is a large variety of potentially revolutionary possibilities for enhancing human performance in military scenarios. In the short-term, selected pharmaceutical and dietary means appear quite realistic, but the former must only be used once adequate controlled studies have been done to verify efficacy and safety. On a slightly longer time scale, it appears that compact, sensor-based implants and advanced drug delivery systems will not only be feasible, but broadly applicable. Finally, in the long-term picture, it is likely that direct neural interfaces will play an important role, perhaps with shorter-term applicability in animals.

DSRC STUDY ON IMPROVING HUMAN PERFORMANCE

La Jolla, CA, July 14 - 15, 1997

Gregory Kovacs

Objective: Explore enhancements to human performance via pharmacologic/ nutritional, and implantable means.

Medical Context: Treating healthy people.

DoD RELEVANCE

- Modulation of endurance and strength.
- Improvement of cognitive functions, reflex speeds, etc.
- Protection against hypoxia, injury.
- Metabolic modulation (“hibernation”).
- Prophylaxis against some CBW agents.
- Physiologic monitoring for feedback (dehydration, bends, etc.) and for history.
- Fast, direct connections between electronics and the nervous system (10 - 20 years from now).

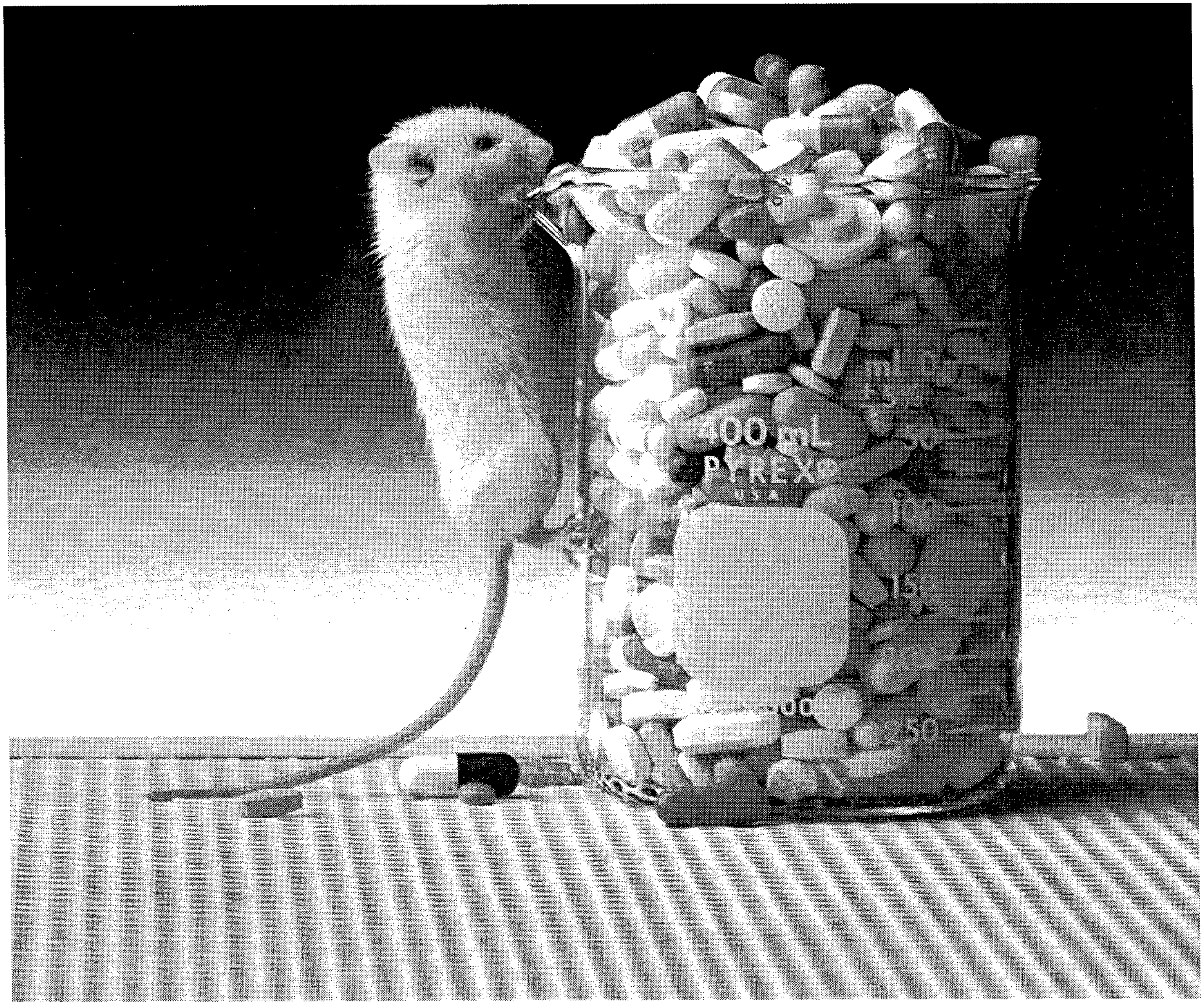


Photo by Mel Lindstrom

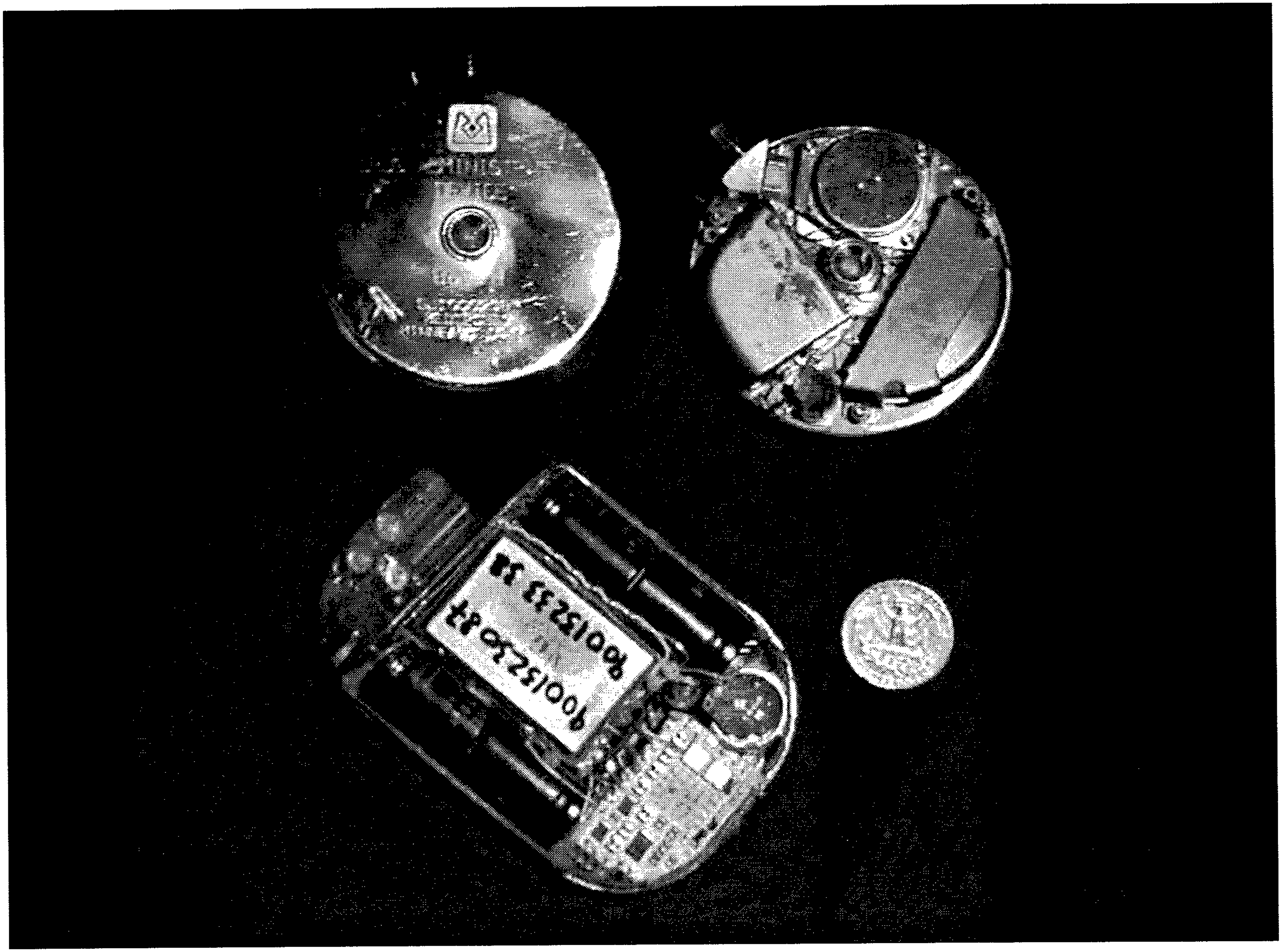
DSRC Study: Improving Human Performance

Pharmacologic/Nutritional Modulators

- Many pharmacologic agents currently exists that could have near-term impact on DoD operations.
- Rigorous, scientific testing must be done (efficacy, interactions, side effects, “pay back”).
- Anectodal evidence (e.g. “smart drugs”) should be viewed with major skepticism.
- Nutritional efforts are low-tech but with potentially large impact.
- Much can be learned from the study of hibernation of animals, in which normal genes are expressed unusually (ultimately leading to drugs?).
- Many enhancement/prophylaxis mechanisms are possible.

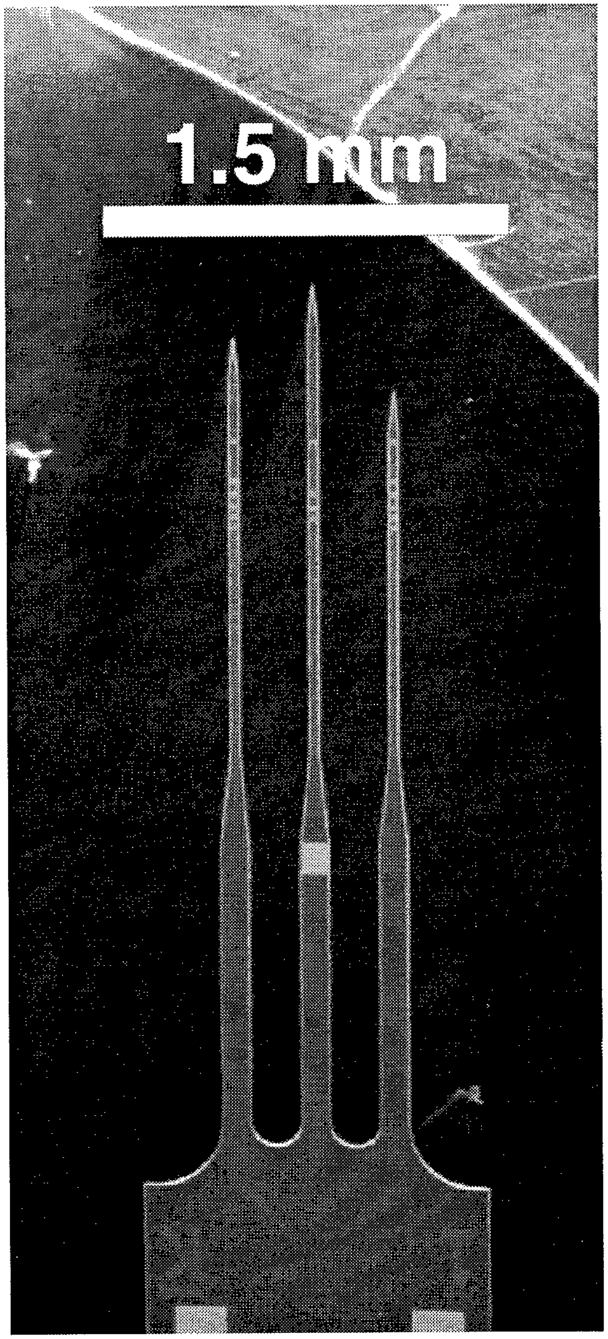
Pharmacologic Agent Delivery

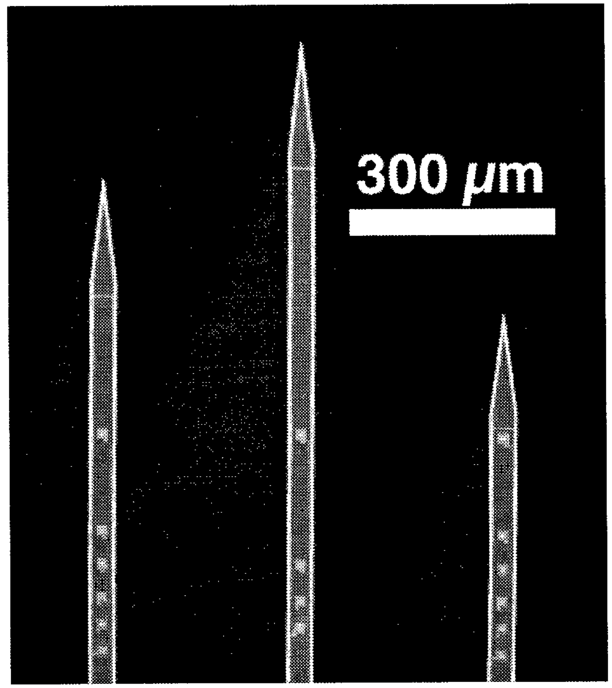
- Two categories of delivery system: organic ("smart gels") or electromechanical ("drug pumps").
- Required drug doses are much smaller when released into the body, allowing small reservoirs to operate over extended periods.
- Organic methods would allow for controlled, slow release that can be turned on and off or engineered to be *automatic* in response to a threat or physiologic change.
- Implantable mesoscopic pumps (existing) allow for programmable dosing with manual override, but are large.
- Much smaller pumps are on the way, but will require more work on MEMS, fluidics, materials and pharmaceuticals.
- Not all pharmaceuticals scale suitably, or are unstable (can perform in situ synthesis using pumps).
- This is a short- to near-term capability.

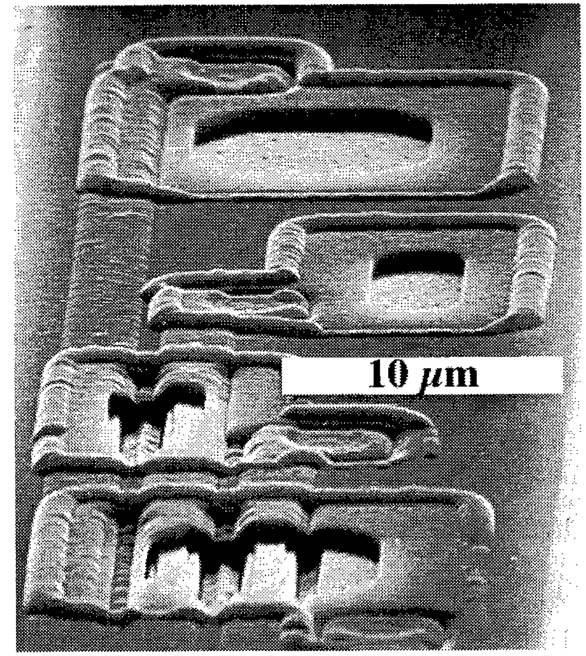


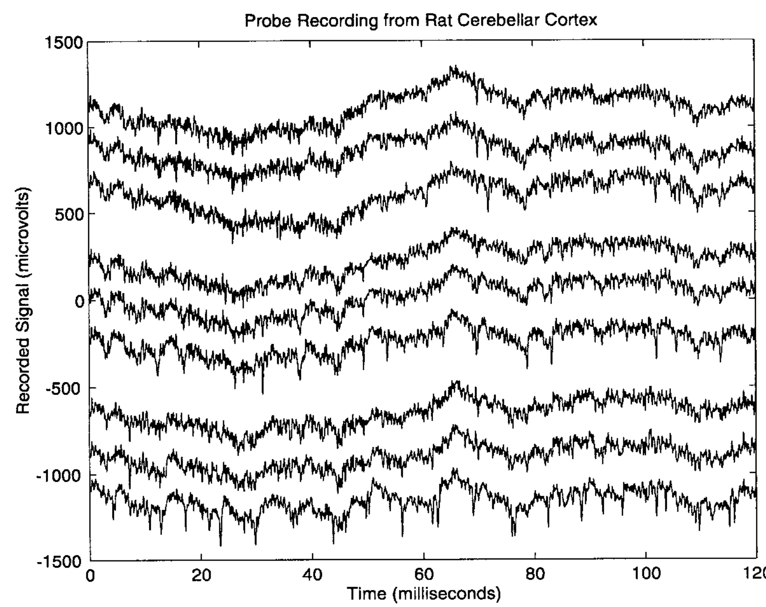
Mesoscopic Implants

- Current military doctrine prohibits implants, but case-by-case cost-benefit analysis may suggest their use in some settings.
- The sensing environment is far richer beneath the skin than outside of it.
- Simple, sensor-based designs have great promise as physiologic monitors and recorders.
- They could provide feedback in dangerous situations (decompression, cold water dives, dehydration).
- They could provide a record of injury and physiologic state for arriving medics.
- Identification/tracking are also possible functions.
- This is a near-term capability, with a lot of key technology in the commercial sector.









DSRC Study: Improving Human Performance

Microscopic Implants

- These devices are direct, high-resolution (single cell level) interfaces to the nervous system.
- 25+ years of research funded by NIH.
- Covert communication channels could be realized.
- Sensory augmentation may be possible.
- Low latency machine/vehicle control could be feasible (motion prediction in monkeys already demonstrated).
- This is a long-term ($\approx$ 20 years) capability, having first to be demonstrated in handicapped individuals, where the functions are restorative rather than augmentative.

Key Technology Limiters

- Pharmacologic Enhancers
  - Scientific studies of efficacy/safety/side effects/"pay-back"
  - FDA approval?
- Drug Delivery
  - Drug stability, engineering of "smart gels," power.
- Mesoscopic Implants
  - Power source density insufficient
  - Sensors/fluidics for in vivo exposure (low drift, accurate)
- Microscopic Implants
  - Need proof-of-concept in humans with disabilities before even considering for healthy personnel.
  - Materials, packaging, power.

Opportunities

- Simple and effective performance enhancement should be possible using pharmaceuticals and nutrition, but careful validation is necessary.
- Advanced "reactive" enhancement/prophylaxis possible with reactive organic systems, or sensor-based drug delivery systems.
- If justified in terms of cost-benefit, could use implantable physiologic monitors for feedback/ recording of problems and "flight recorder" operation.
- Long term: direct connections to the nervous system after proving out in humans.

IMPROVING HUMAN PERFORMANCE

Study Organizer: G. Kovacs

Monday, July 14, 1997

July 14, 1997	• Pharmacologic/Biologic Modulators of Human Performance
Morning Session	• Neuropharmacologic agents (alertness, cognition, etc.)
	• Metabolic modulators
	• Anti-aging technologies
	• Hibernation
	• Others
8:00 a.m. – 8:40 a.m.	**Performance Enhancement for DoD Needs Through Pharmaceuticals** Dr. Ward Dean (Private Practice)
8:50 a.m. – 9:30 a.m.	**Advanced Pharmaceuticals for Cognitive Enhancement** Mr. Steven Fowkes (Cognitive Enhancement Research Institute)
9:40 a.m. – 10:20 a.m.	**What We Know About Hibernation and How It Applies to Humans** Prof. Sandy Martin (University of Colorado Health Services)
10:30 a.m. – 11:10 a.m.	**Topic Title TBD** - (complimentary talk on hibernation to Prof. Martin) Prof. Matthew Andrews (North Carolina State University/Genetics)
11:20 a.m. – 11:50 a.m.	**Advanced Drug Delivery Technologies** Dr. Lisa Brannon-Peppas (Biogel Technology)
12:00 p.m. – 1:30 p.m.	Working Lunch, Discussions

Key Questions:

- What are critical DoD needs in this area?
- For sustained operations or unusual circumstances, are there pharmaceutical agents that could provide significant enhancements in the near future?
- What are the "payback" costs for using "enhancers"?
- What (if anything) is industry doing that DoD could use and might need to know more about?
- How are the procedures for testing/screening these pharmaceuticals (which don't correct any ailments) different from those now used to test/screen conventional drugs?
- What are the predictions for the short-term and long-term future?

IMPROVING HUMAN PERFORMANCE

Study Organizer: G. Kovacs

July 14, 1997	• Prospects for Implantable Devices
Afternoon Session	• Current technologies and their projected evolution • Physiologic monitors • Drug delivery systems • Tissue-based implants
1:30 p.m. – 2:10 p.m.	**Implantable Drug Delivery Systems** Mr. Markus Haller (Medtronic, Inc.)
2:20 p.m. – 3:00 p.m.	**Drug Delivery Systems** Dr. Stephen Jacobsen (Sacos, Inc.)
3:10 p.m. – 3:50 p.m.	**Overview and Potential for Implantable Electronic Devices** Dr. Peter Tarjan (University of Florida/Biomedical Engineering)
4:00 p.m. – 4:40 p.m.	**Prospects for Implantable Devices for Healthy Individuals** Dr. Tibor Nappholz (Telectronics, Inc.)
4:50 p.m. – 5:30 p.m.	**Implantable "Black Boxes" for Human Use, and Other Futuristic Implant Ideas** Mr. Lou Halperin (Medtronic, Inc.)
5:30 p.m. - 6:30 p.m.	**Discussion**

Key Questions:

- What are the "wish list" features for implants (trauma support, pharmaceutical injection, physiologic monitoring, etc.)?
- Under what circumstances would implants be worth it (cost-benefit analysis) if they could provide significant enhancement?
- What comes next after pacemakers and their kin?
- Is there a need for a "black box" ("flight recorder") for humans?
- Can engineered tissues +/- microimplants be made realistic in the near future?
- What are the real limiters in developing implants? Consider materials properties, surface treatments, bio/electronics interface, size and packaging, cost, etc.

IMPROVING HUMAN PERFORMANCE

July 14, 1997

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IMPROVING HUMAN PERFORMANCE

July 15, 1997

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UNINHABITED VEHICLES

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DSRC CoChair: J. Williams

DARPA Chair: S. Wax

DSRC Participants:
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Other Participants: A. Epstein, N. Hagood, T. Weisshaar

Objectives

(i) Identify common technology themes and research needs for the next generation of air, land and underwater vehicles envisaged by the DoD.

(ii) Prioritise those technologies most critical to the implementation of these UV systems.

(iii) Within each technology, specify the nature of the challenge and suggest opportunities for solutions.

Given the emphasis on DSO/ETO technology, human/machine interface issues have not been addressed, even though they are understood to be central to UV implementation.

DoD Relevance

The focus of the study was on vehicles yet to be developed. While ongoing programs were carefully reviewed, the study has excluded current high altitude long endurance (HALE) missions and underwater vehicles fielded by the Navy. In order to learn about present platforms and to explore next generation systems, two workshops were held (in January and April), with input from DARPA/TTO, DARO, all of the services, Lincoln Labs., Airforce SAB, and various consultants. These were followed by specialised workshops on structures, power/propulsion annd actuation technolgies, as well as site visits to Lockheed and TRA, where sysytems are under development, and to organisations concerned with the development of next generation systems.

The consequent emphasis was on the following systems.

(i) UltraHALE vehicles capable of very high altitude (above 60kft) flight with long endurance, as well as uninhabited combat vehicles (UCAVs).

(ii) Uninhabited small rovers and air vehicles, especially their locomotion and power.

(iii) Uninhabited underwater vehicle propulsion systems

Technology Summary

1. Technologies Addressed

Four key technology areas relevant to DSO and ETO were identified in the first phase of the study. These comprised:

(i) Power And Propulsion

(ii) Actuation And Motor Technologies

(iii) Affordable Ultralight Structures

(iv) Sensors And Avionics

The last topic was not explicitly addressed in this study, but juxtaposed with the DSRC study on Multifunctional Dynamic Materials Systems.

2. Status and Challenges

The importance of **weight** and the **integration** of the various functions needed to realise the mission requirements are generic. An attempt at quantification has been made by establishing key metrics for the relevant technologies. Within the parameter space defined by these metrics, the requirements for various UVs have been superposed. In this manner, critical technologies and pathways to implementation have been identified.

For *power and propulsion*, the metrics are power, duration and mass or volume. However, system specifics influence comparisons between competing approaches. For large UAVs, gas turbines are unequivocally the best sources of power and propulsion. (Although, there are limits at very high altitude, say above 65kft). For small aerial and land vehicles, analagous assessments require of mass as a function of energy diagrams (fig 1).

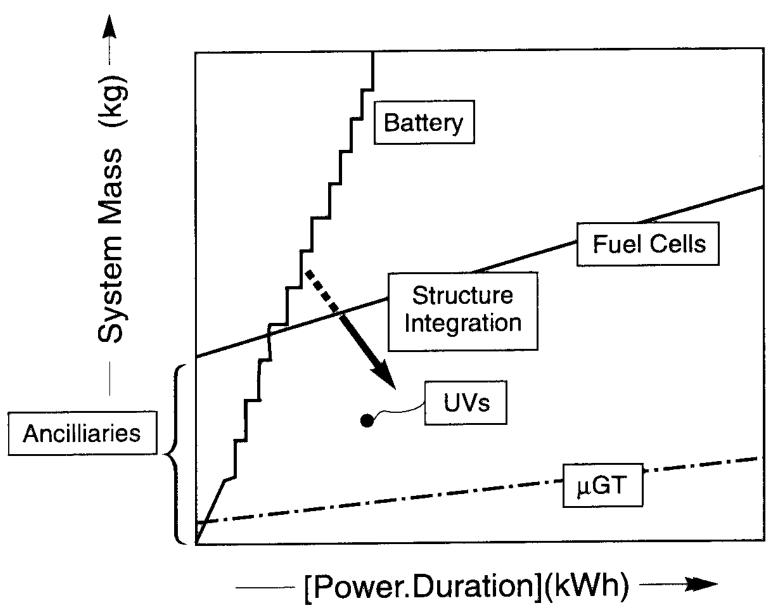
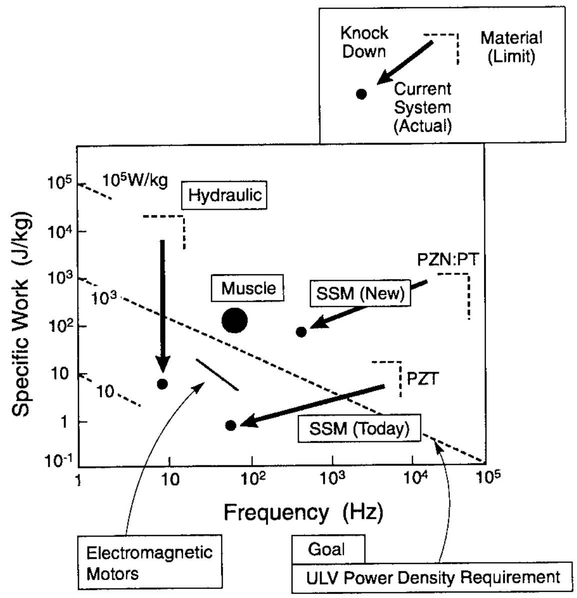


Fig 1. Energy, system mass diagram. The requirements for typical small UVs are superposed.

For *actuation*, the metrics are the specific power output, the authority and the conversion efficiency (electrical to mechanical). A specific work against frequency diagram (fig2a) addresses the power output. The authority superposes in a system specific manner (fig 2b).



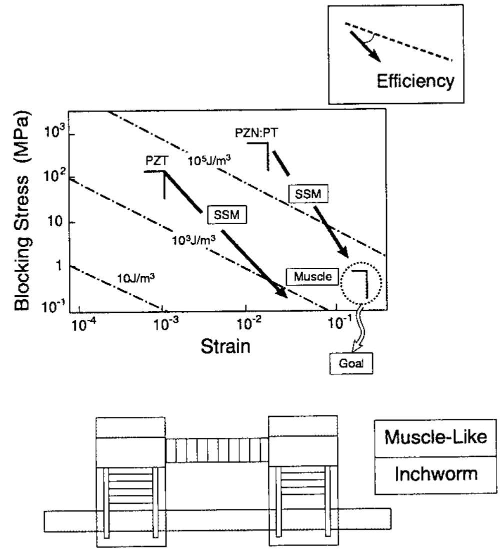


Fig 2a. A power density diagram for some actuation systems showing the theoretically achievable levels of specific work and frequency, as well as vectors governing the "knock-downs" that occur in practice because of the losses and the mass of the ancilliaries. SSM refers to solid state motors made from piezos, with "new" pertaining to single crystal PZN:PT.

Fig 2b. An authority diagram for the solid state actuation systems indicating the vectors associated with motor efficiencies.

For lightweight structures, loiter time, mass and mission fuel fraction are the relevant parameters. These are manifest in a diagram that plots the increase in loiter time per decrease in structural mass as a function of the mission fuel fraction (fig 3). HALE vehicles are designed to have large values of the latter, whereupon major benefits in loiter time accrue from composite design and manufacturing stategies that decrease the mass.

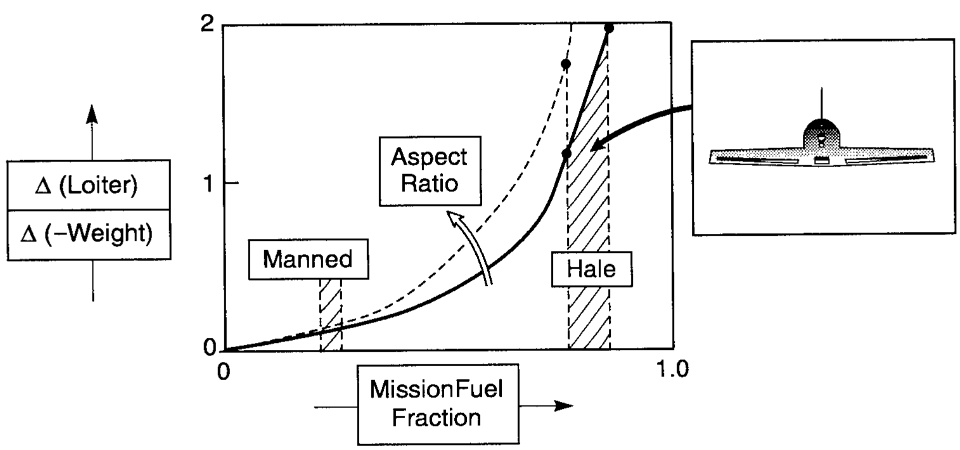


Fig 3. The effect of structural mass on the loiter time as a function of the mission fuel fraction, with typical ranges for HALE and manned vehicles indicated.

While the technology issues differ substantially as the vehicle mission changes, the following generalizations pertain. Lightweight structure is important for HALE UAVs. Power is critical for all small vehicles. Actuation and motors are crucial for locomotion and, in some cases, propulsion, especially for small vehicles. The subsequent discussion embraces these generalizations.

The enabling technologies for next generation vehicles, summarised in Table I, are elaborated below.

Table I. Technology Enablers for Next Generation Uninhabited Vehicles

Actuator Systems	High authority piezoelectrics. Solid state motors: design cocepts and interfaces. Field-responsive polymers.
Lightweight Power And Propulsion	Integrated metal/air battery and fuel cell technologies. Micro gas turbines. Direct methanol fuel cells. Active propulsors. Flexible lightweight photovoltaics.
Structures	Low cost, ultralight composites. Design-To-The-Limit strategems. Subelement testing protocols.

2.1 Power and Propulsion

Missions for small air and land vehicles are severely constrained by presently available power and propulsion systems. That is, for the expected power and mission duration, power delivery systems are excessively massive. A mass/energy diagram (fig 1) embodies the separate roles of the efficiency (the slope) and the parasitic mass of the ancilliary components (the intercept).

Batteries have low energy density, but no ancilliary components. They are the system of choice (lowest mass) for short duration missions. Conversely, fuel cells are preferred for longer durations; the undesired mass of the ancilliaries is offset by their high efficiency. In both cases, the study has revealed that reductions in mass can be achieved by *integrating* the power source with the structure. Moreover, for fuel cells, further reductions in mass can be expected upon developing a liquid fuel supporting technology.

Micro gas turbines and generators have highly desirable mass/energy characteristics. They should be efficient and have low mass ancilliaries. However, they are the newest of the power and propulsion technologies and consequently there are remaining questions about

the conepts viability, but these are being addressed through near term demonstration programs. Should the demonstrations provide compelling evidence of the overall viability, a rapid exploitation strategy would be appropriate. Among the technologies being neglected through the demonstration phase are materials beyond SiC (such as oxides, etc.), more sophisticated microfabrication technologies, and heat engines other than turbines.

Superimposing the requirements for prototypical missions for small UVs (fig1) gives further insight. One is for the Point Man ULV, which requires about 500W for 4h, and the other for a mini UAV, which requires of order 50W. It is apparent that micro turbine generators would satisfy the mass goals. Moreover, in some cases, batteries may suffice if they are well integrated with the structure and exploit new lightweight photovoltaic recharging concepts. For fuel cells to be applicable, supporting technologies need to be developed that reduce the parasitic mass of the ancilliaries and the fuel storage.

HALE UAVs and UCAVs use turbofan or turbojet propulsion systems, which are efficient and reliable. The only problem arises at very high altitude where turbocharged internal combustion engines may be a good option. These engines are being developed by NASA.

2.2 Actuation

Actuation requirements are dependent on function and mission: that is, whether they are to be used for locomotion, propulsion, ailerons, etc. It is surmised that the realisation of authority and power density levels exhibited by muscle would satisfy most requirements. Indeed, the actuation requirements for the Point Man land rover are essentially those found for muscle. The major discriminator among systems is the power density/bandwidth metric (fig 2a). On this diagram, the theoretical maximum power densities are indicated, as well as the considerable "knock-downs" that occur in practice. This happens because of the mass of the ancilliary components and the frictional/viscous losses. The practically achievable power densities(<200W/kg) are all deficient relative to the most power dense muscle (>2kW/kg). This conclusion has been illustrated for hydraulic systems, electromagnetic motors and solid state (piezo) motors, but it also applies to SMAs, etc. For existing motors, there are additional problems with the authority (fig 2b). That is, even at the maximum efficiencies found in practice, as the stroke is increased to the levels needed to simulate some types of muscle, the force that can be delivered drops appreciably below that achievable with the best muscle.

The figures also indicate the potential for attaining the actuation goals with new systems. In particular, the "gap" between capabilities and requirements would be addressed should the new PZN:PT single crystal ferroelectrics exhibit their expected characteristics when incorporated into motors. That is, power densities and authorities comparable to those for muscle appear to be achievable, even upon using the same "knock-down" factors and efficiencies found for motors made from conventional PZTs. However, for such motors to be realised, high frequency "burn-up" problems arising at the frictional interfaces must be solved by improved design and by creating more efficient interfaces.

For small vehicles, another important factor is the size scaling, which is particularly favourable for PZN:PT. Namely, at small size, the non-hysteretic nature of the material allows operation at higher frequencies, enabling increased power densities without sacrificing authority.

2.3 Structure

High altitude long endurance (HALE) UAVs have a very high fraction of fuel to gross take-off weight. The design of HALE aircraft is particularly sensitive to changes in either payload or structural weight. In the design stage, an increase in structural efficiency parlays into relatively large gains in mission goals such as range or loiter time, or, alternatively, into a smaller vehicle. Spacecaft design involves analagous considerations. High structural efficiency is less critical to the design of uninhabited combat vehicles (UCAVs). Moreover, it is much less important for manned and commercial aircraft and is a lower priority in these sectors.

Some use of low cost, light weight structural concepts for polymer matrix composites has been made in the two HALE UAVs under current development. In particular, Dark Star has an all composites structure configured in a manner that departs from that for manned aircraft. Low temperature curing has been exploited to produce a relatively low cost composite fuselage built up from just a few large sections. Nevertheless, because of constraints on the development costs, innovations in low cost manufacturing (such as e-beam curing) and light weight design were limited. In deference to their unmanned status, structural efficiency in these aircraft has been increased as a consequence of design based on a safety factor of 1.25, as opposed to 1.50 for manned craft. On the other hand, this gain was at least partly offset by the highly conservative material property values used, in part, because of the large uncertainty in these properties and a poor understanding of their relationship to structural failure. In short, some advantage of low cost, light weight composite construction has been incorporated in the two UAVs under construction, but the full potential is far from realized.

Structurally efficient, low cost UAVs will require designs which fully exploit the unmanned character of the vehicles. The constraints imposed by the FAA on Global Hawk and Dark Star appear to work against structural efficiency and may not be rational. Due consideration should be given to the expected flight lifetime of the UAV and the alteration in extreme loads this might entail. For example, design to withstand a gust level expected on the average of only once every ten thousand hours of flight becomes questionable for an aircraft whose life expectancy is much less.

A new paradigm in low cost polymer matrix composites construction is emerging based on low cost tooling, especially coupled with low temperature (including e-beam) curing. It is finally leaving behind the "black aluminum" syndrome. Large unitary sections are fabricated and co-cured, substantially reducing the number of joints and incorporating features such as integral stiffening. Low temperature curing permits inexpensive tooling, including expendable male tooling. Scaled Composites has demonstrated this approach by producing one and two-piece fuselage sections. Large sections of low temperature co-cured composites are incorporated into Dark Star. The mechanical coupon properties (e.g., elastic modulus and strength of small test specimens) of these composites are lower than those of conventionally processed polymer matrix composites. Component shape precision is also generally inferior. The former is traded against the reduction in the number and weight of joints, which comprise a significant weight fraction in conventional (black aluminum) composite structures. In many instances, problems with shape precision can be circumvented by clever design.

The new paradigm addresses head-on the issue of low cost aircraft structures. The technical challenges to implementing unitary composite structures include: (i) analysis tools and testing protocols which evaluate the structural failure modes and loads and enable design-to-the limit strategems, (ii) new design and manufacturing solutions specifically tailored to the approach and (iii) improved low temperature cure polymer matrices.

2.4 Bioinspired Locomotion

Current robots are balanced by virtue of having a stable center of mass. They are consequently sluggish and slow. Recent work has utilized a biologically-inspired approach to locomotion that starts with an understanding of biomechanics and of the coordinated responses of the pods. This has lead to an understanding that animals are not stably balanced and require the action of several muscles to stand erect. The resulting 'dynamic' stability is important for many aspects of performance of two-legged animals, particularly their agility and speed. Designing robots that maintain a dynamic balance will require multiple muscle-like actuators, new design principles for distributing the actuators, mechanisms to measure balance, and control systems to coordinate this information with the actuator responses. The pressure sensors currently used by robots to handle objects (i.e., picking up an egg) are limited both in performance and in number relative to those used by biologic systems. Integrated sensors on the feet and skeleton of the robot are required to interrogate terrain and even to detect instabilities in the underlying terrain during locomotion. These robots require on-board control systems that can collect and process information from distributed sensors and coordinate many actuators with a frequency of 10 Hz. The most compelling technology requirement is that for muscle-like actuation systems.

3. Technology Opportunities

3.1 Power and Propulsion

For *fuel cells and batteries* to be successfully implemented in small UVs, the use of the most efficient chemistries, coupled with structural integration, appears to be necessary. Metal (Al,Mg,Li)/air battery technologies may be especially appropriate, because the constituents are compact and lightweight. Navy technology could be exploited for this purpose. One integration approach might involve the use of thin pretensioned fabrics made from carbon, alumina or Kevlar fibers as the host for the electrolyte, as well as the anode. The particulates and fluids that perform the chemistry would then be infiltrated using slurry technologies developed for composites (fig 4). These fabrics would be compliant in compression and bending and need to be stretched over polymer composite spars or grids in order to resist aerodynamic loads as well as to support the propulsion unit and the sensors. These skins could be on the wings and fuselage of air vehicles, as well as the body of land rovers.

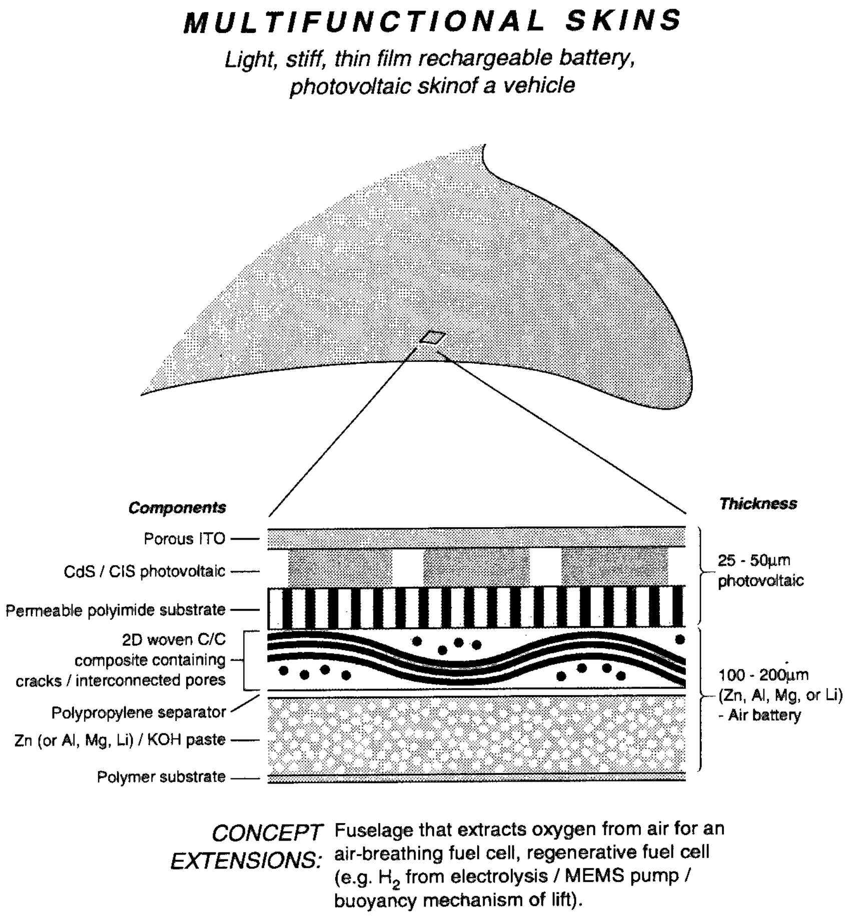


Fig 4. A multifunctional concept for a skin structure able to use flexible photovoltaics for energy collection, a metal-air thin film battery for power storage and a woven carbon fiber fabric electrode to provide structural support.

A further enhancement might be achieved by superposing a photovoltaic skin over the fabric. Flexible thin film photovoltaics with 500W/kg power densities are now available. These could be used to encapsulate the thin film batteries, providing a 200μm thick skin structure (fig 5). For some missions, the photovoltaic would be able to recharge the battery layers in periods of high solar flux and when the vehicle is quiescent. The weight trade-offs may be favourable for missions having these characteristics.

In addition to this benefit from structural integration, the mass of *fuel cell systems* can be further decreased by using liquid fuels (i.e. hydrogen storage is inefficient) and through the development of lightweight microvalves and pumps. Direct methanol cells provide a promising basis for such a development.

Microgas turbines and generators have yet to be demonstrated. However, if the imminent demonstrations are compelling, an investment in those materials that offer the best thermomechanical characteristics would be important. Materials such as SiC and mullite can be made into the required forms by several methods. These range from focused ion beam machining, reactive ion etching, CVD, stamping approaches based on PDMS, tape casting of ceramic slurries to the exploitation of organic ceramic precursors.

Finally, engines that use other thermodynamic cycles remain to be explored.

3.2 Actuation

Solid state motors that use the new higher authority, high bandwidth materials offer great promise for achieving many of the actuation goals for next generation small UVs, particularly for locomotion and, in some cases, for propulsion. The intensive DARPA development of the PZN:PT single crystals could be exploited as the pre-eminent actuation material. The challenges arise in motor designs and new interfaces that address the losses and the high frequency burn-up. When all-solid-state systems are of interest, basic aspects of friction at small, dynamic contacts are crucial. For pump actuators, high pressure microfluidics issues need to be addressed, such as microvalves that minimise viscous losses.

The integration of the linear motors into robotic systems that enable locomotion could be achieved using pretensioned tendons, reminiscent of the actuation modes used in actual muscles. These possibilities are elaborated below. Such motors would also have application as solid state actuators in HALE UAVs and UCAVs, enabling elimination of the hydraulics, which add considerably to the weight of present vehicles. Moreover, being much more efficient than electromagnetic-based systems (the present benchmark) they may also be useful for propelling small air vehicles.

Another role might be in actively controlled propulsors for UUVs, designed to twist relative to the root and, thereby extend the non-cavitating operating envelope.

3.3 Structure

HALE UAVs are in the high fuel fraction mission domain, wherein weight reductions have disproportionally large effects on the achievable loiter time. Consequently, a large benefit accrues from implementing a design and manufacturing paradigm for composites that eliminates conservatism in the joints/attachments and successfully enables realisation of a small safety factor. In particular, there is an opportunity to invest in the design, analysis and manufacturing of low cost composite structures based on low temperature curing. Improvements in polymer matrices for low temperature curing are needed to bring the coupon properties of these composites more in line with those for conventionally processed composites. Success would provide a major breakthrough in composites materials development. Component strength and structural failure modes of composite structures cannot be determined from coupon data. Fiber reinforced composites differ significantly from metals in this respect, and the absence of methods to apprise composites at the component level hinders their introduction. New testing protocols based on component or subcomponents must developed. Methods to analyze failure modes (delamination, splitting, joint failure) and loads exerted on composite components must developed in parallel. These protocols and analysis tools will be applicable to design with any fiber reinforced polymer matrix composite, but they are especially needed in the development of light weight, low cost structures for HALE UAVs and UCAVs.

3.4 Structural Integrity Probes

The introduction of UAV's with all-composite airframes offers new opportunities for integrity evaluation within a design-to-the-limit strategem. Present designs are dominated by joints, because of the considerable variability in the loads at which they delaminate. This adds conservatism. While delaminations are often non-catastrophic, they redistribute the loads and eventually cause problems that lead to failure on subsequent missions. Integrity probes provide an emergent ability to sense the delaminations. This probing capability al-

lows less conservatism in joint design, with advantageous implications for weight and loiter time, but it requires that the analysis tools noted above be put in place.

The sensing possibilities arise from the emerging capability to embed non-invasive fiber sensors or taggants into composite structures and use them to monitor the strain history of the structure, as well as the incidence of strength degrading delaminations. This is made possible by a new micromolding method for placing grids onto small diameter (10μm) fibers that minimally perturb composite integrity.

The incidence of delaminations at joints might be probed by high resolution ultrasonic measurements made with an embedded fiber optical system. One approach is illustrated in Fig.5. Locally doping a fiber with a rare earth creates a region of strong optical absorption. This absorption results in local heating and thermal expansion of the fiber. If a short optical pulse is used, the ensuing abrupt thermal expansion causes the generation of cyclindrical elastic disturbances with sharp risetimes. A Fabry-Perot interferometer or Bragg grating positioned collinearly with the exciting fiber would detect the ultrasonic signal, enabling measurement of its time of flight and therefore, the change in velocity due to delaminations.

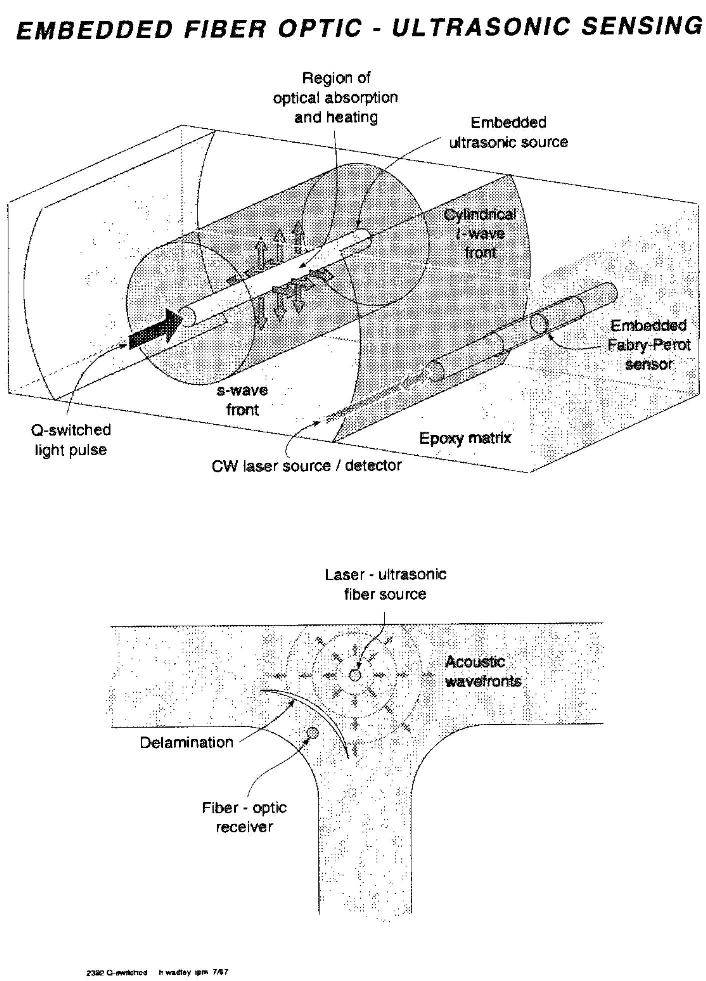


Fig 5. A laser ultrasonic approach for insitu measurement of delaminations.

The detecting fibers monitor the static strain in the structure. But, it also appears possible to use dispersed particles for monitoring the residual strains in the matrix. Magnetostrictive materials like Terfenol, Samfenol or rapidly solidified MetglassTM all have high magnetostrictive constants and a strongly stress dependent permeability. By also embedding thin copper electrodes, it would be possible to measure a change in the RF impedance caused by residual strain changes. Such changes would signify the incidence of nearby structural delaminations.

3.5 Bioinspired Vehicle Embodiments

A two-legged land rover (fig 6) could be a well-suited testbed for the development and integration of the new technologies highlighted above. For the maintainance of balance, the robot will require fast response muscle-like actuators and a greater number of these actuators together with sensors that either measure balance in the gravitational frame of reference or measure strain and pressue in the skeleton and feet of the robot. The number and distribution of actuators and sensors are guided from an understanding of the biomechanics of an animal model. In order to run rapidly and to navigate complex terrains, the robot requires integrated sensors that can interrogate the underlying terrain and recognize unstable and dynamic footings. The robot will require a hierarchial control system to actuate foot stability, leg movement, and balance. Moreover, the on-board processing must continuously process the sensor feedback and instruct the actuators at several Hz.

Winged insects inspire many UAV concepts in the 5cm size range. Such vehicles are ideally suited for surveillance in many urban and densely forrested mission environments. Compared with fixed wing air vehicles in this size range, the flapping of insect wings seemingly produces 2-4 times the lift achievable from steady aerodynamic flow over the surface. The mechanisms responsible for the extra lift are still controversial, but the measured lifts are not.

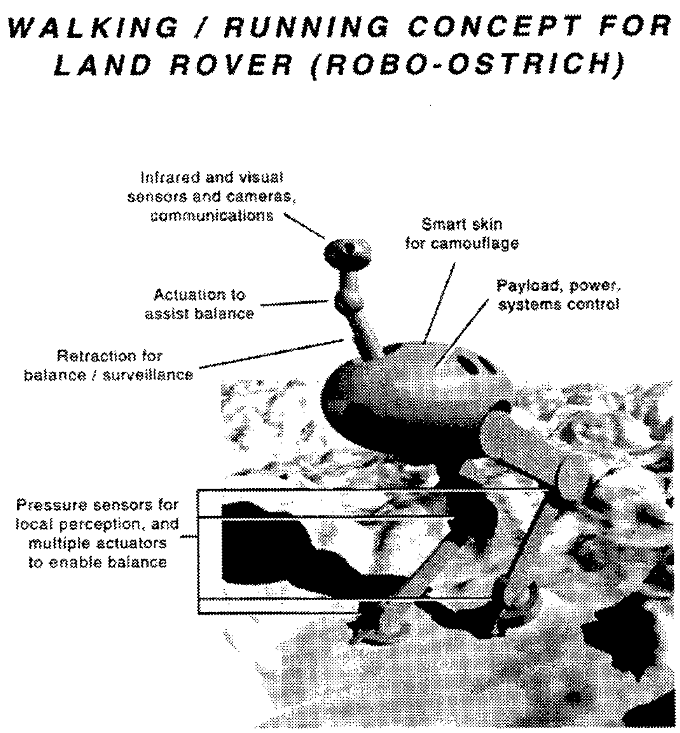


Fig 6. A model concept for a two-legged land robot based on the ostrich.

Conclusions

For next generation UVs, four areas promise more than an evolutionary advance in technology.

1. Many potential missions are constrained by power densities. Past and present DARPA funding addresses key issues, such as efficiency and mass. The new challenge is to integrate these systems with the structure and to develop a support technology for the ancilliaries, such as microvalves.

2. Commercially available actuation systems are not capable of achieving the power densities and authorities needed for next generation vehicles, typically 1kW/kg. There is a major opportunity to exploit the DARPA investment in the new single crystal ferroelectrics to develop solid state motors that have performance characteristics comparable to muscle. Such a development could satisfy locomotion goals as well as provide compact solid state actuators for HALE UAVs, UCAVs, and manned aircraft (military and commercial) that eliminate the heavy hydraulic actuators now in use. An investment in motor design and in new interfaces is needed for this purpose.

3. Lightweight composite structures have demonstrable benefits for the loiter time achievable with HALE UAVs. Full advantage of this opportunity requires a design-to-the-limit strategem, based on new test protocols and analysis tools. It also entails the fabrication of large unitary sections, preferably using low temperature curing (including e-beams) to significantly reduce costs. Low temperature curing polymers with higher toughness are enabling.

4. Development of an understanding of biologically inspired locomotion mechanisms for small systems could translate into concepts that use the above technologies in the most efficient manner.

APPENDIX I

BIOINSPIRED LOCOMOTION

M. Mrksich and H. Wadley

Biology provides countless examples of meter-sized machines capable of autonomous operation in challenging environments. Animals combine many features and strategies that are critical to their performance. Certain of these elements have been incorporated into modern land robots—most commonly, the mechanical geometry of a multipod—but they represent a somewhat casual view of animal mechanics. There are several design elements inherent to animal systems that, if properly understood and applied, will enhance dramatically the performance of next generation land robots. This appendix summarizes three key issues that require increased attention.

Perception. With every step, animals test the properties of the terrain to establish the stability, sinkage and friction of the surface. They can then modify their route in order to avoid insurmountable barriers or change the gait to reduce the chances of slipping or falling. A similar capability is needed in robots to enable locomotion in most realistic environments. The sinkage and friction of a surface can be determined by measurements of distributed forces. For sinkage, the foot could be equipped with a pad that rests lightly on the terrain and provides a reference for changes in height or force of the foot. Friction can be assessed by recognizing patterns in force and acceleration of the legs during locomotion.

Biomechanics. The legs and joints of many robots have been designed to mimic the mechanical structure of an animal. In most cases, these same designs have ignored the important materials aspects of the biomechanical systems. Many animals, for example, reduce the metabolic cost of running by utilizing the elastic properties of muscles, tendons and bones distributed in their bodies. Moreover, different gaits are used to optimize the passive dynamics of the system: in humans, a common example is the transition from walking to jogging to running as the forward velocity increases. For robots, the use of compliant elements could simultaneously increase speed and provide substantial energy savings. Implementation of these strategies requires a better understanding of passive dynamic operations in legged robots and integration of compliant materials into the joints and skeleton.

Control Systems. As the number of degrees of freedom of a multi-legged robot increases, so to does the complexity of the control systems. Behavioral and neurobiological studies of appropriate animal models can identify effective gaits for coordinating a large number of multi-jointed legs. Insects, for example, are capable of continuing to locomote despite wide variations in terrain, external loads, and damage to their body. This approach has been used to design a hexapod robot that uses gaits mimetic of the spider to walk at different speeds, to maneuver over objects and to locate stable footholds on irregular surfaces. The hexapod uses a distributed control system based on the insect locomotion wherein each leg is controlled by a concurrent process that uses local information from load sensors, inhibition between adjacent legs, and excitation from rear to front to generate metachronal waves: importantly, the hexapod could still walk stably if excitation was removed or if a single leg was paralyzed. The realization of robots having a greater number of joints and actuators will require a better understanding of the trade-offs between central, hierarchical and distributed control systems.

Uninhabited Vehicles

A. Evans

S. Wax

J. Williams

Next Generation Vehicles

Air, Land, Sea

Hale ⟺ Combat

Large ⟺ Micro

State-Of-Art Technology

Technology Challenges

Mission Enabling

Capability Enhancement

GENERIC THEME

Weight	Power
Cost	

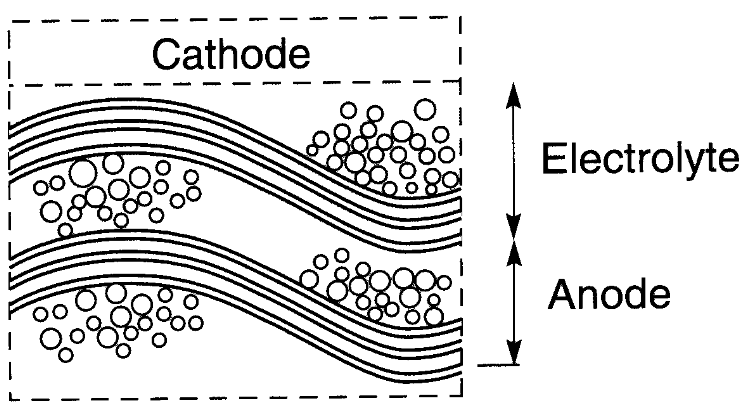
Must Integrate Everything

Power	Structure
Power	Actuation

Some Fledgling Ideas

Need Analysis

Load Bearing Battery



Stretch Fabric

TECHNOLOGIES ADDRESSED

Workshops	
DARPA	January 20
Navy	April 16
AF	
Task Groups ⟹	Feb. - July
Power / **Propulsion** ⟹	Epstein / Williams
Actuation ⟹	Cross / Hagood
Structure ⟹	Hutchinson / Weisshaar / Budiansky
UV Concepts ⟹	Wadley / Mrksich
Electronics ⟹	Heuer Study

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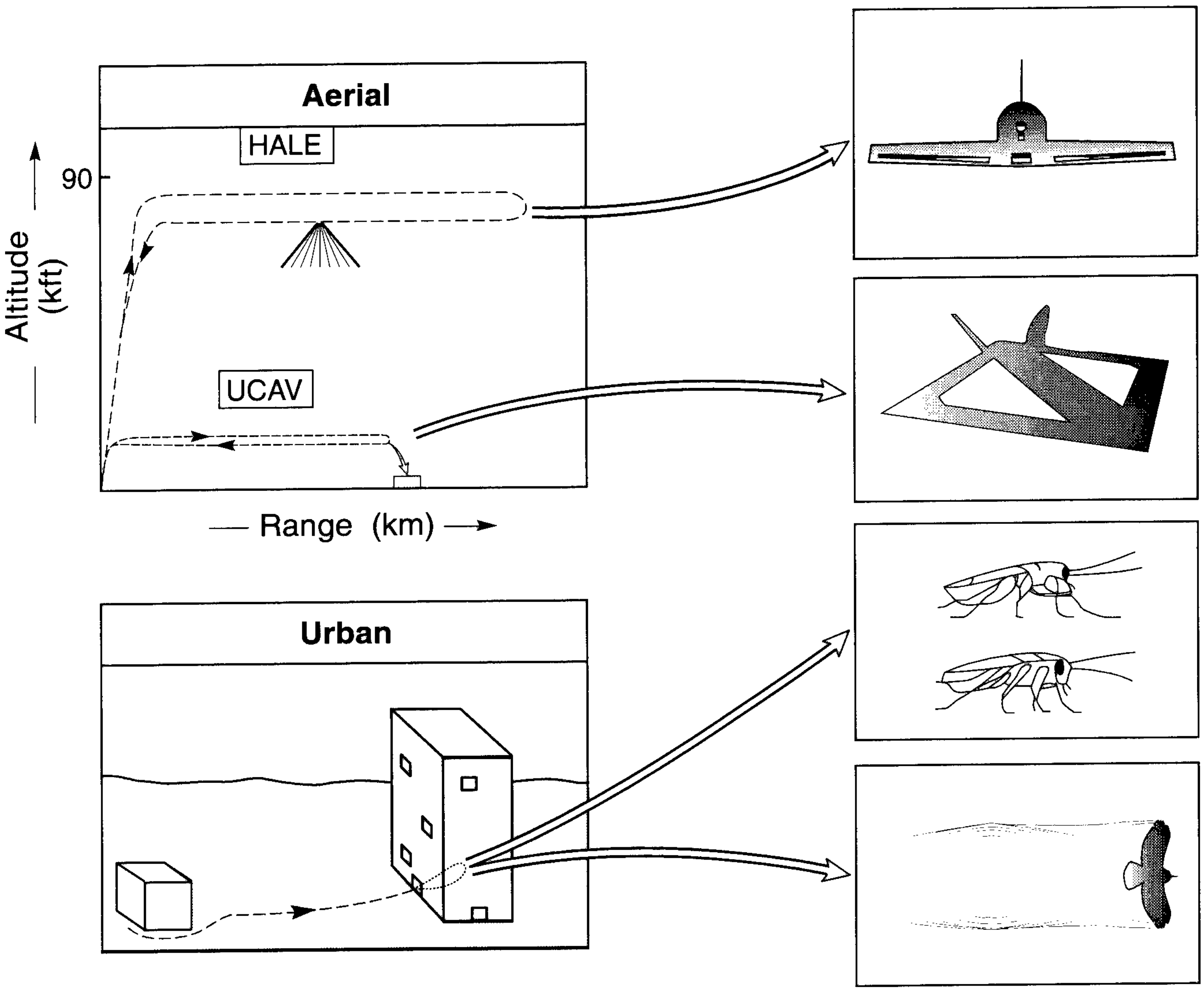
DoD RELEVANCE

UNINHABITED VEHICLES



STRATEGY

Establish Metrics For Comparing Technology With Requirements

Power / Propulsion	Power	Duration	Weight	
Structure	Fuel Fraction	Duration	Weight	
Actuation	Power	Torque	Weight	Bandwidth

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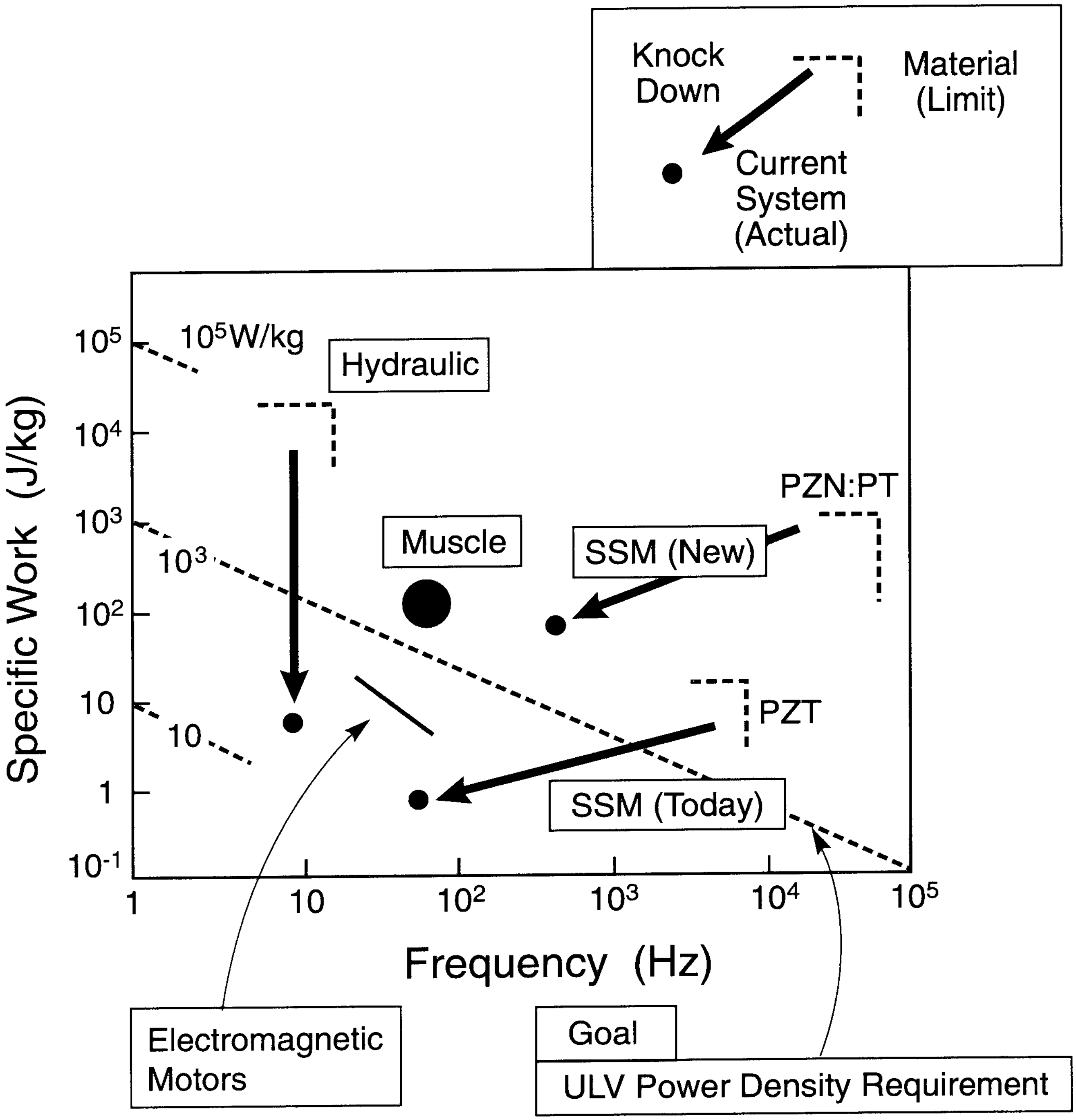
ACTUATION SYSTEMS

Metric I ⇔ Power Density



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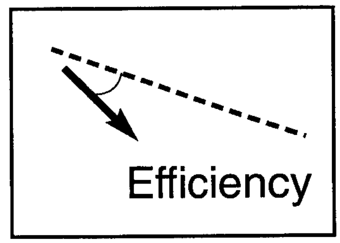
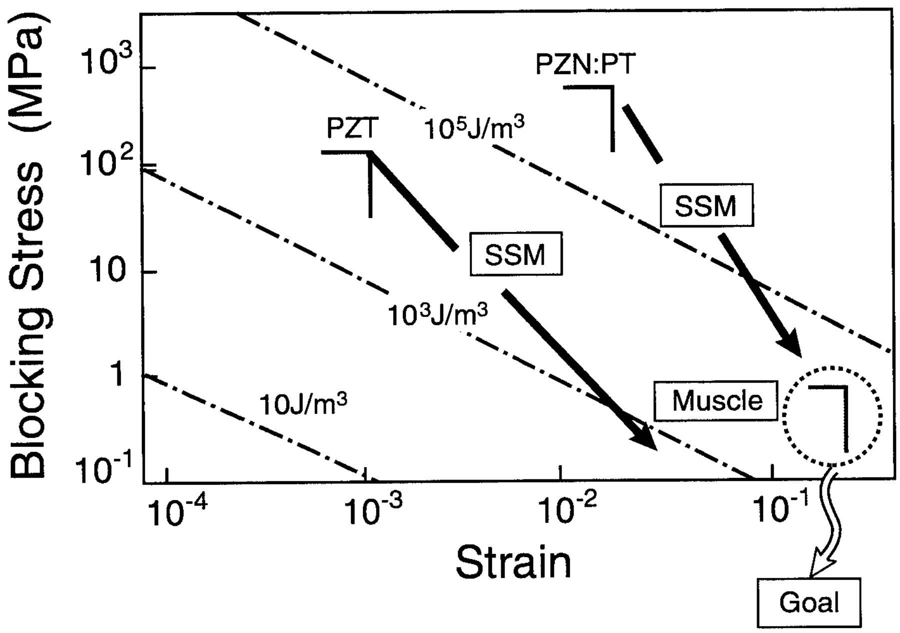
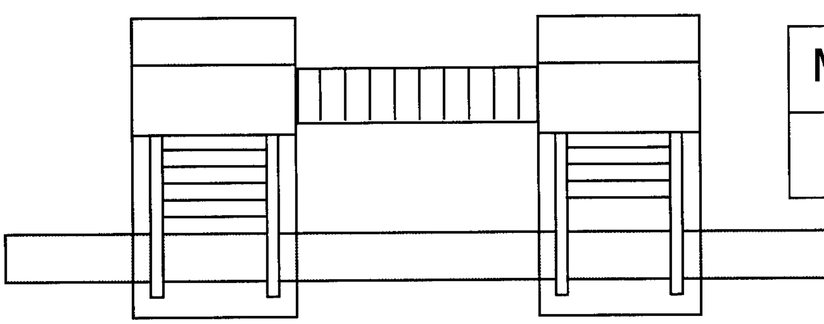
METRIC II ⟺ **AUTHORITY**

Force	Displacement
Torque	RPM







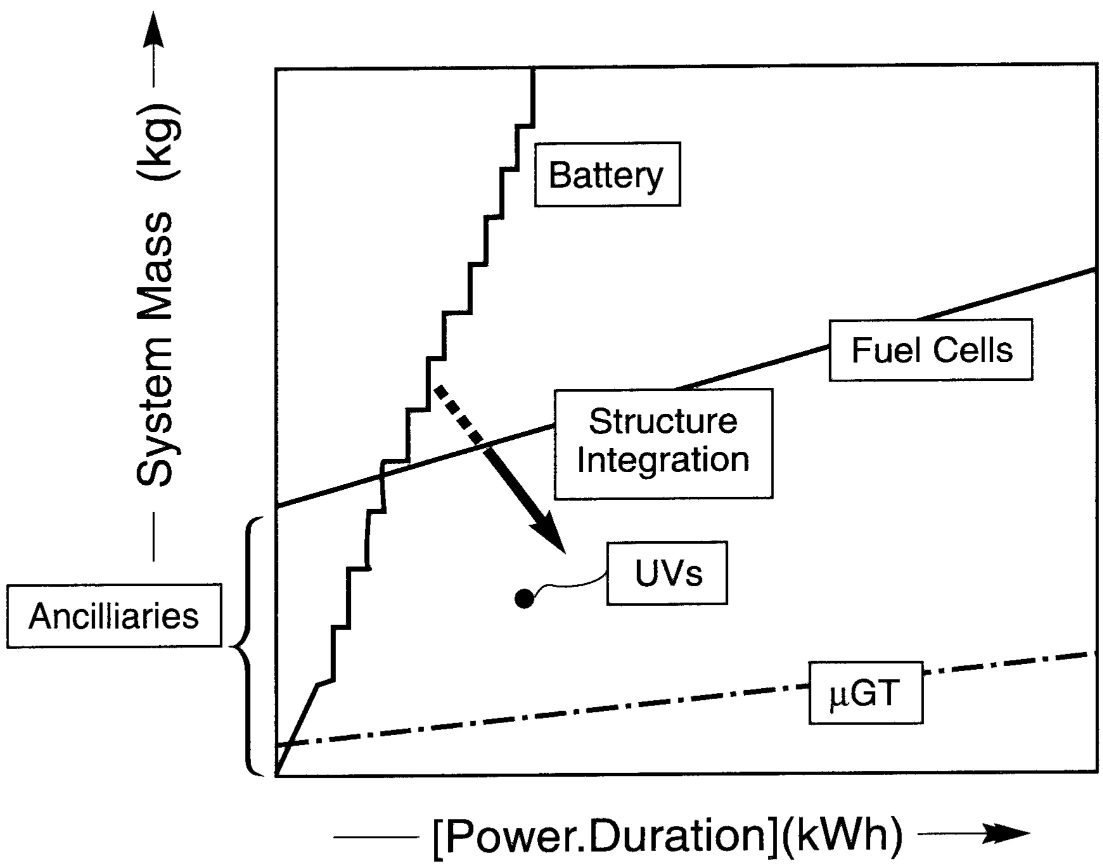
Muscle-Like

Inchworm

Figure 3B

POWER AND PROPULSION FOR SMALL LAND AND AIR VEHICLES

Mass	Energy	⇒	Power



Integration With Structure	→	Fuel Cells
Mass of Ancilliaries		**Batteries**

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POWER AND PROPULSION SUMMARY

Fuel Cells

Batteries

Need Integration And Support Technology

Microengines

Generators

Demonstrations Imminent

Materials Technology Immature

Oxides	SiC	Si_3N_4

Other Engine Technologies Unexplored

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ACTUATION SUMMARY

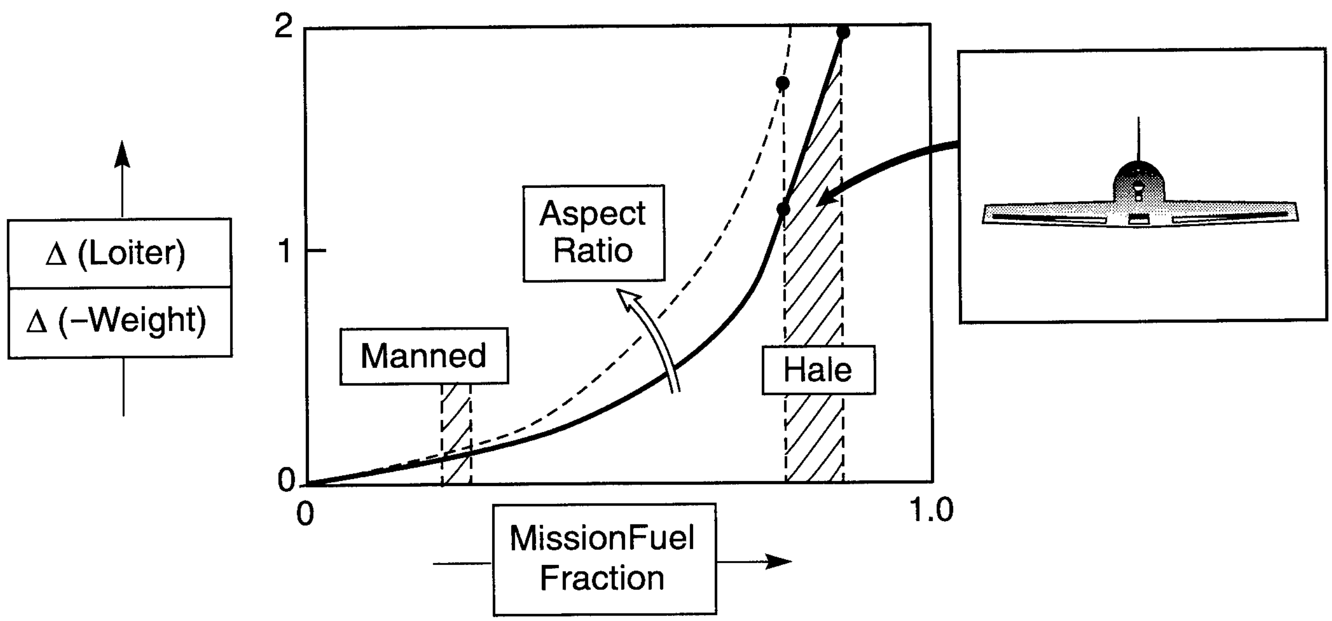
Presently Available Actuation Systems Inadequate For Muscle-Like Performance

Required Capability Seems Achievable Using Solid State Motors With New Materials Plus Novel Drive and Interface Configurations

New Polymers Are A Promising Option

DESIGN AND MANUFACTURING FOR HALE

Issue — High Gain For Weight Reduction
Space Craft



Status

New Manufacturing/Design Paradigm

But	Conservative Design
	Manufacturing Variability

Opportunities

Design-To-Limit Strategy

Testing/Simulation Protocol

Polymers	Low T Cure
Mission Sensors	"Active" Composites

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STRUCTURE SUMMARY

Hale Vehicles Benefit From Ultralight Structure

Design-To-Limit (1.1?) Strategem

New Manufacturing/Design Paradigm Immature

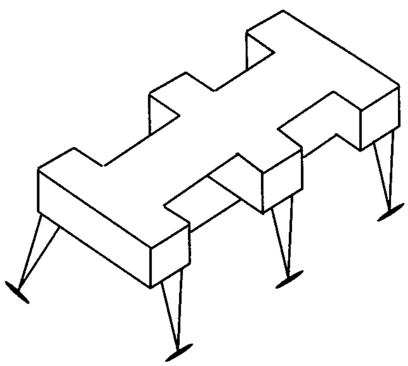
Deficiencies Exist In
Design Codes
Testing/Simulation Protocols
Low T Cure Polymers

MECHANISMS AND ALGORITHMS FOR LOCOMOTION AND HOVERING

Present Systems

Land Rovers Too Slow $(1 \rightarrow 10 ms^{-1})$

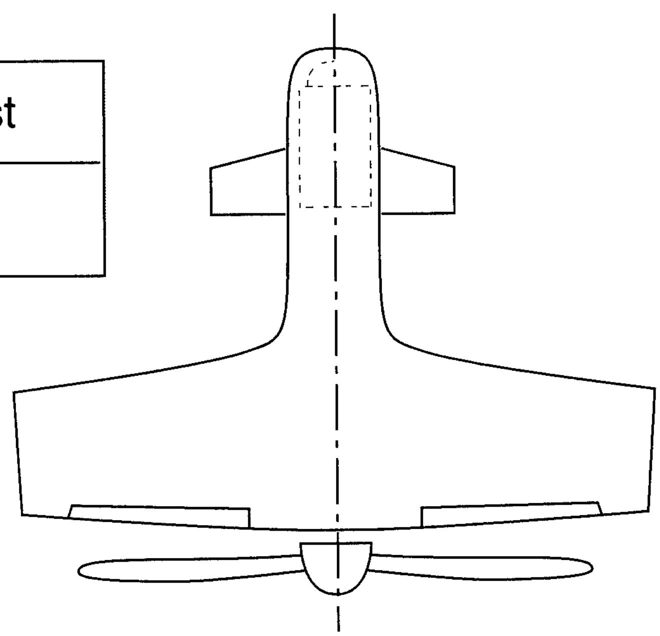
$6 \rightarrow 2$ Legs With Balance



Multiple Actuation Modes

Microair Vehicles Too Fast

Need To Hover



Flapping Flight

CONCLUSIONS

Four Areas Require More Than Evolutionary Advance In Technology

Power For Everything

- Integration is Critical
  - Structure
  - Power

Actuation For Locomotion

- Muscle-Like Solid State Motors
- Interfaces and Design
- Polymers (?)

Lightweight Structures For Hale Loiter

- Design-To-Limit Strategem
- Testing/Simulation Protocols
- Polymers

Locomotion Concepts

- Mechanisms
- Algorithms

Biologically Inspired Land Robots

Modes of Locomotion	Relevant Terrains
Wheels	Desert
Treads	Forest
Pods	Jungle
	Urban

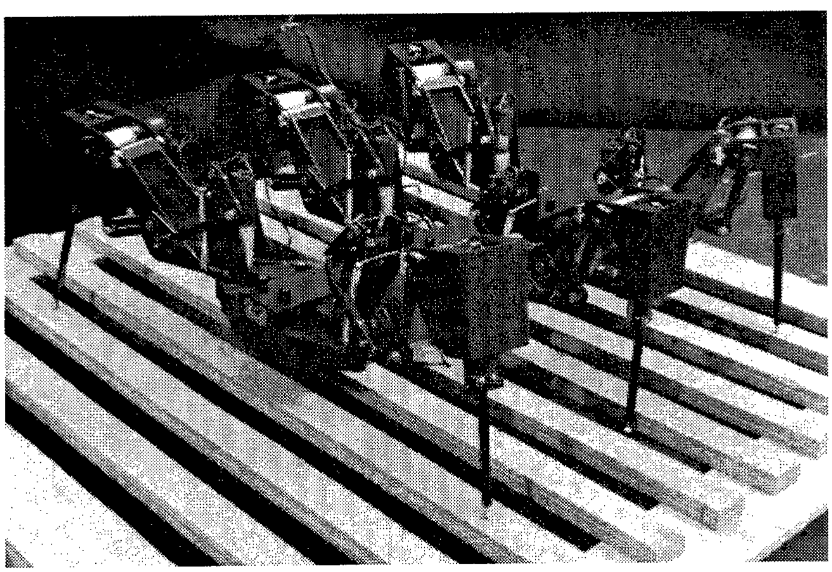
Biologic designs have the principle advantage that they enable locomotion in most terrains, including unknown and unstable terrains.

Development Limited By:

Demands on volume placed by actuation and power systems Control systems for multiple joints
Perception of environment
Efficient energy conversion

Spider-Inspired Crawling Robot

- Active compliance distributes load evenly
- Searching behavior documented for locust walking used to locate footholds on irregular terrain Walking in a continuum of gaits from slow wave to fast tripod
- Biomimetic gaits for turning and crabbing
- Distributed control system is robust to unexpected changes in environment and to injury



Enabling Technologies Required for Walking Robots

• *Actuation*	increased response time reduced volume requirements systems of actuators
• Dynamic Balance	stability during rest and movement
• Perception	strain, pressure and gravitational distributed sensors
• Materials	biomechanics of elastic and compliant skeleton and muscle
• System Controls	on-board processing to collect information from distributed sensors and coordinate many actuators --hierarchical and distributed controls

Supplementary Information

WORKING AGENDA

Uninhabited Vehicle Study
Study Organizer: Anthony Evans

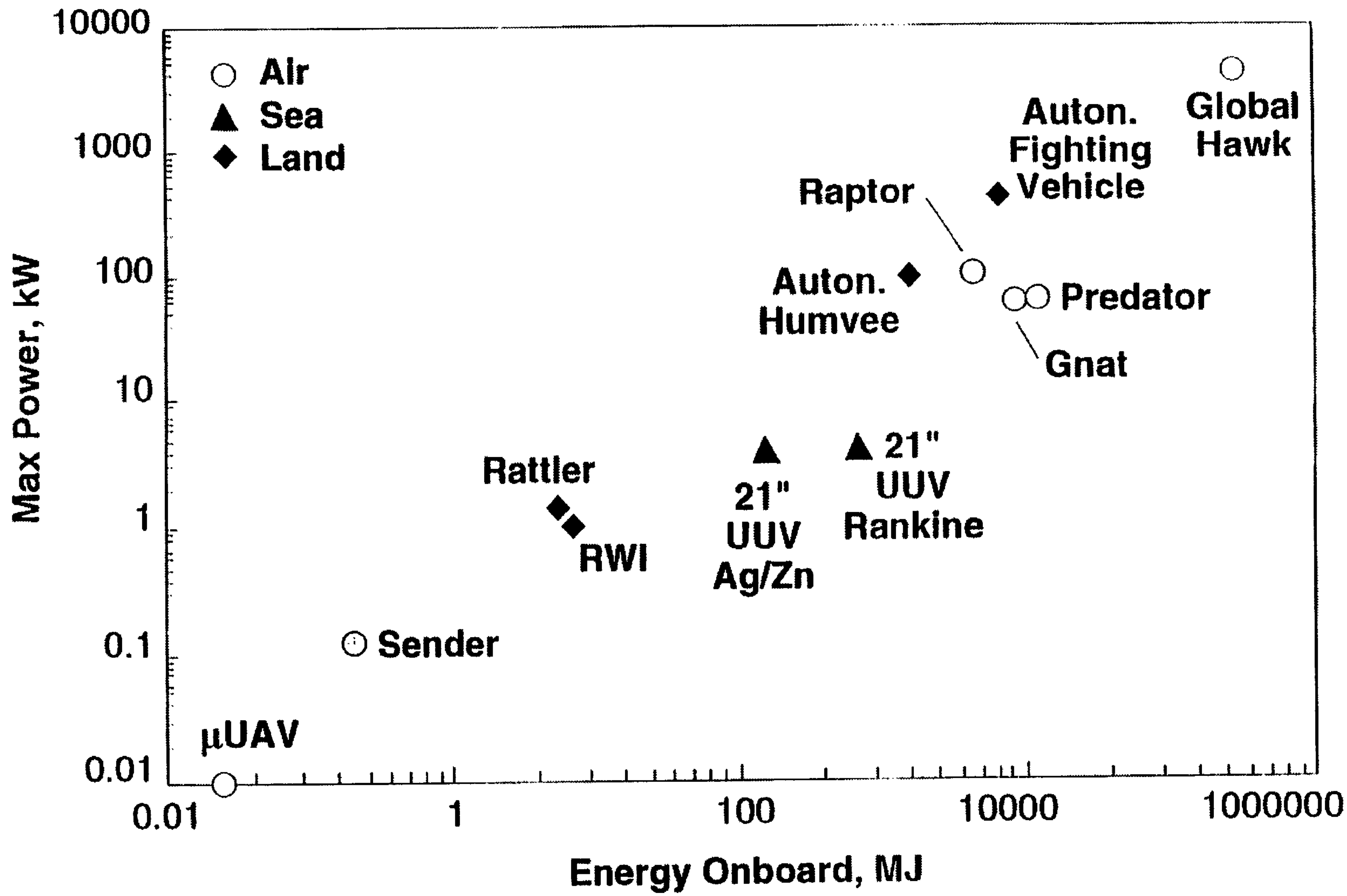
Wednesday, July 16, 1997

8:00 a.m.	**Objectives and Structure of Study** Anthony Evans (DSRC) Steve Wax (DARPA)
8:30 a.m.	**Summary of Uninhabited Vehicle Missions and Systems** Steve Wax (DARPA)
9:00 a.m.	**Next Generation Systems** H. Wadley (DSRC), Milan Mrksich (DSRC)
10:15 a.m.	**Power and Propulsion** A. Epstein (MIT), Jim Williams (DSRC)
Noon	**Lunch**
1:00 p.m.	**Actuation Technologies** E. Cross (DSRC), N. Hagood (MIT)
3:00 p.m.	**Break**
3:15 p.m.	**Minimum Weight, Affordable Structures** J. Hutchinson (DSRC), T. Weisshaar (Purdue), B. Budiansky (DSRC)
5:15 p.m.	**Ajourn for the day**

Thursday, July 17, 1997

8:00 a.m.	**Technology Priorities and Integration Issues** A. Evans (DSRC) J. Williams (DSRC), S. Wax (DARPA)
Noon	**Adjourn**

PROPULSION AND POWER SYSTEM CHARACTERISTICS



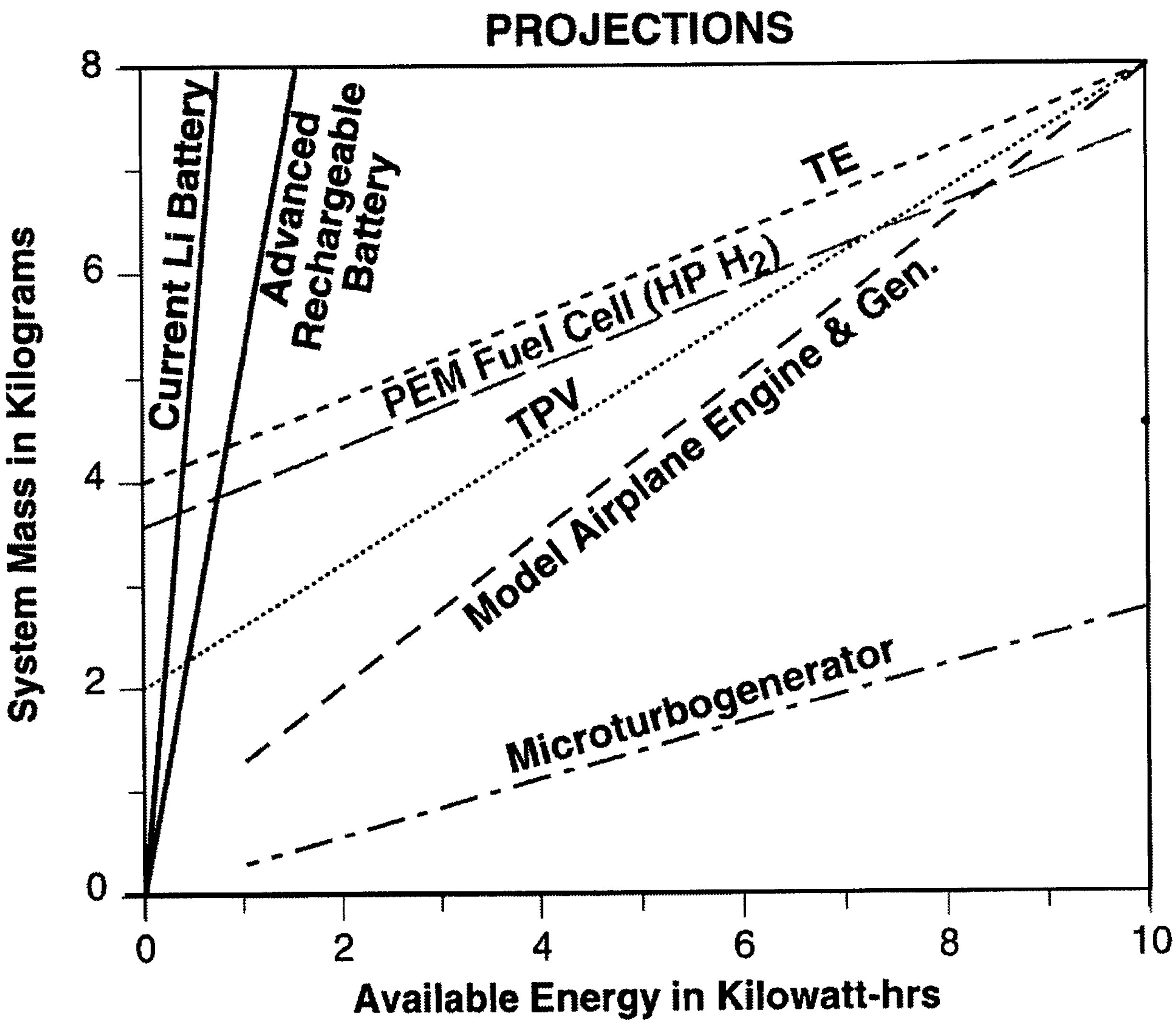
FUEL CONSUMPTION COMPARISON

Diesels	Kg/kwh
Very large diesel (10~20 Mw)	0.18
Automotive diesel (75 KW)	0.20
Small (7.5 KW)	0.23
Spark Ignition	
Automotive engine (75 KW) (best)	0.30
(average over cycle)	0.45
(idle)	0.6
Small IC Engines	
1-8 hp	0.45-0.65
Small Gen Sets	
Below 6 KWe	0.6-0.9
8 KWe	0.31*
68 KWe	0.23*
Gas Turbines	
"G" class frame machines (250 Mw)	0.23
Trent (51 MWe)	0.21(g)
RB-21 1(30 MW)	0.22 (g)
RB-211 (27 MWe)	0.23(g)
F'T8 (19 MW)	0.22 (g)
LMl600 (15 MW)	0.24(1)
570-K (Allison) (4850 KW)	0.28
T-64 (GE) (2275 KW)	0.29
RTM-322 (RR) (1560 KW)	0.27
AGT-1500 (1120 KW)	0.29
ST6T-76 (1075 KW)	0.39
IE831-800 (Garrett) (600 KW)	0.42
Light helicopter gas turbine (500 KW)	0.38
SATCON ST-260 (263 KWe)	0.37
SATCON ST-60 (63 KWe)	0.45
Automotive gas turbine goal (50 KW)	0.28
Elliott Energy Systems (45 KWe)	0.28
Capstone (24 KWe)	0.27
Nissan Dynajet 2.6 (3.1 KW)	1.12

Combined Cycle Power Plants		
Old	37% efficient	0.23
Current	50% efficient	0.17
Future	60% efficient	0.14
Fuel Cells		
Small H_2 fueled (0.1 - 1 Kwe) (45% eff)		0.06
Natural gas fueled (10 KWe)		0.17
H2 fueled (@gaseous H_2 = 5% of storage wt)		1.0
DMFC (50 W)	1.4	
MIT Micro Gas Turbine		
Initial unit, H_2 fueled (0.02 KWe)		0.45
Later developments, JP-4 (0. IKWe)		0.28
Batteries		
$LiSO_2$ (primary, current SQA)		5.7
$LiSOCi_2$ (primary - future?)		3.3
NiCd (rechargeable)		21
Lithium ion (rechargeable)		10-12

*Diesel
1 gal/hphr = 41.4kg/kwhr
1 lb/hr/shp = 0.609 kg/kwhr
Heating value of JP-4 = 0.0835 kg/kwh
Installed large GT's ~$250 simple cycle, $500/kw combined cycle
(l) liquid fuel, (g) gaseous fuel

TYPICAL SYSTEM MASS vs. ENERGY
- 50 Watt Point Designs -



TYPICAL SYSTEM MASS vs. ENERGY
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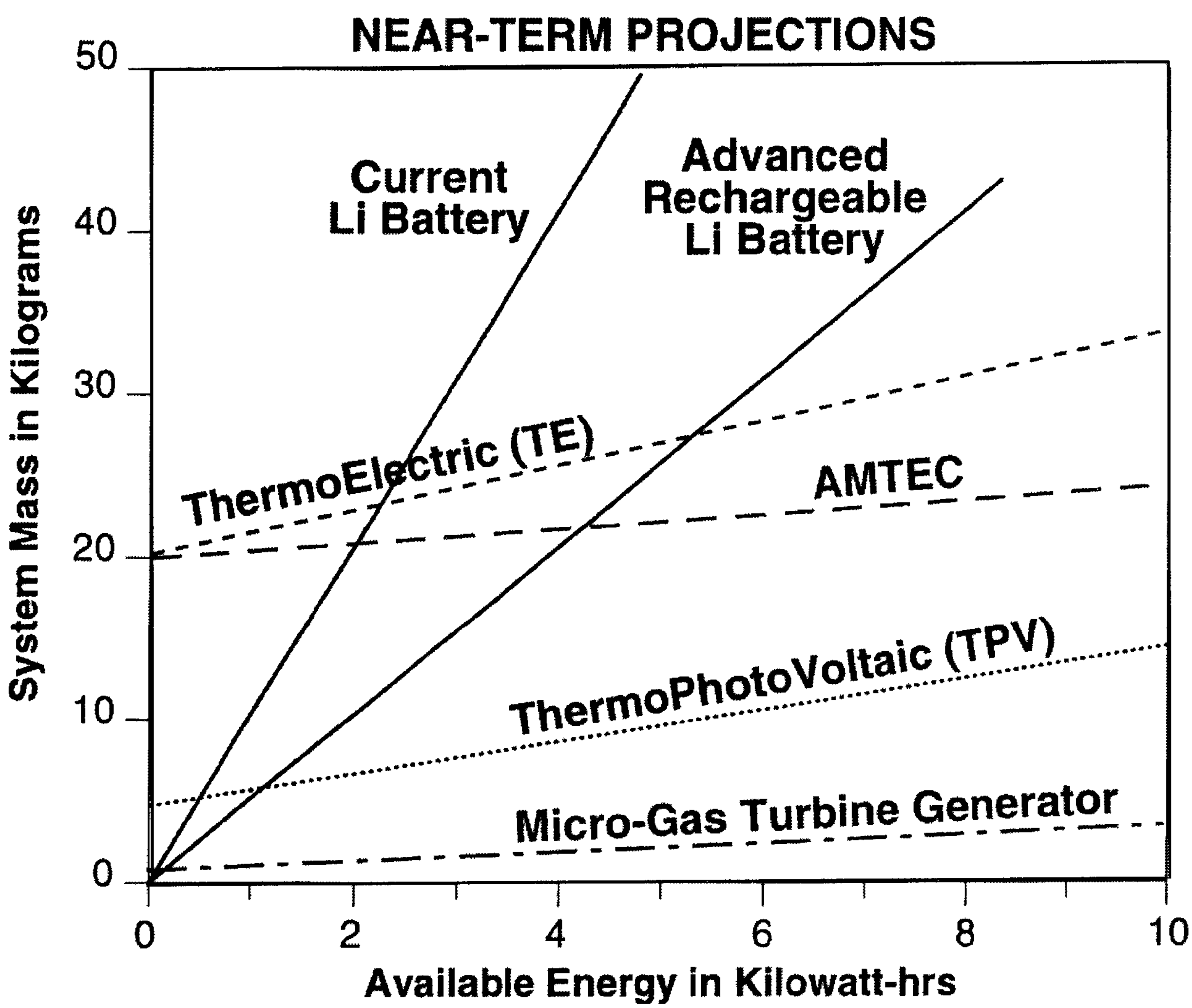

POWER AND PROPULSION FOR SMALL LAND AND AIR VEHICLES

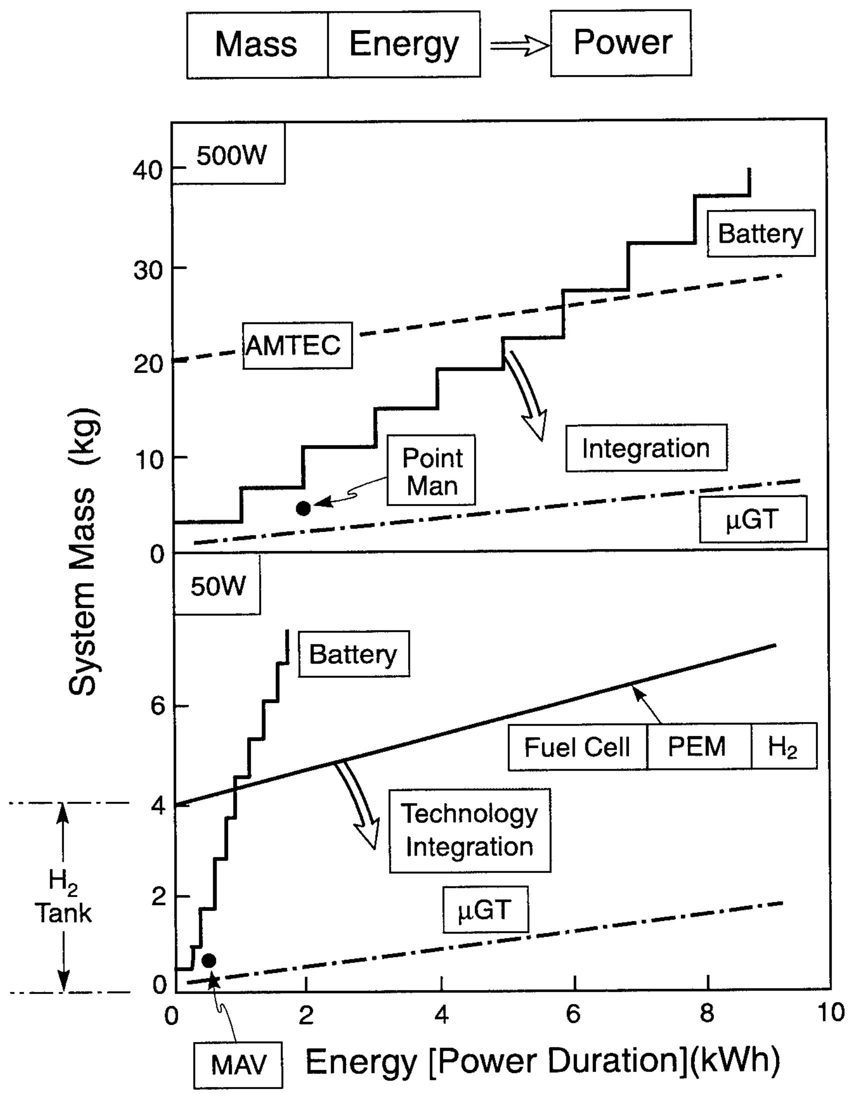

Figure 2

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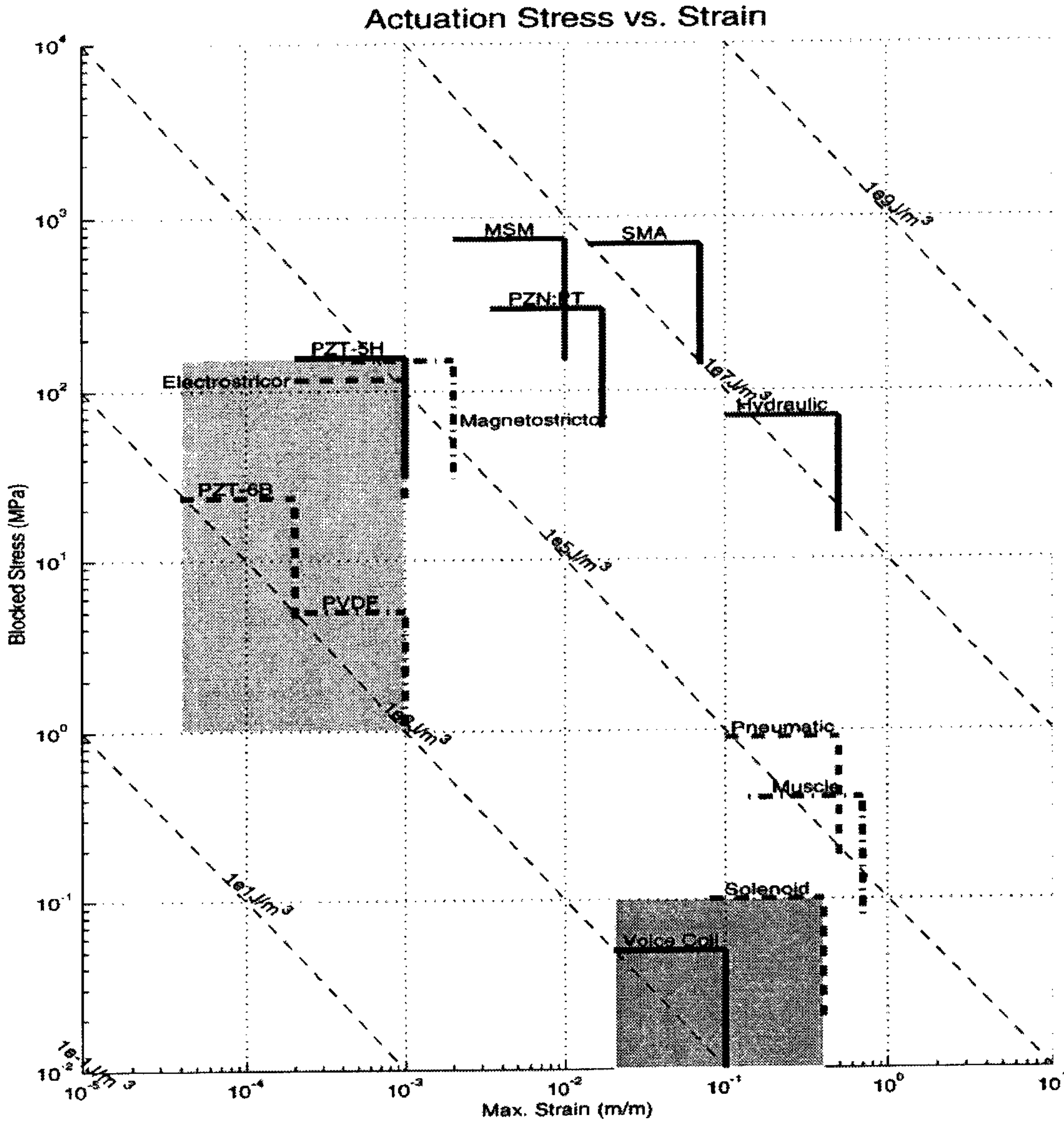
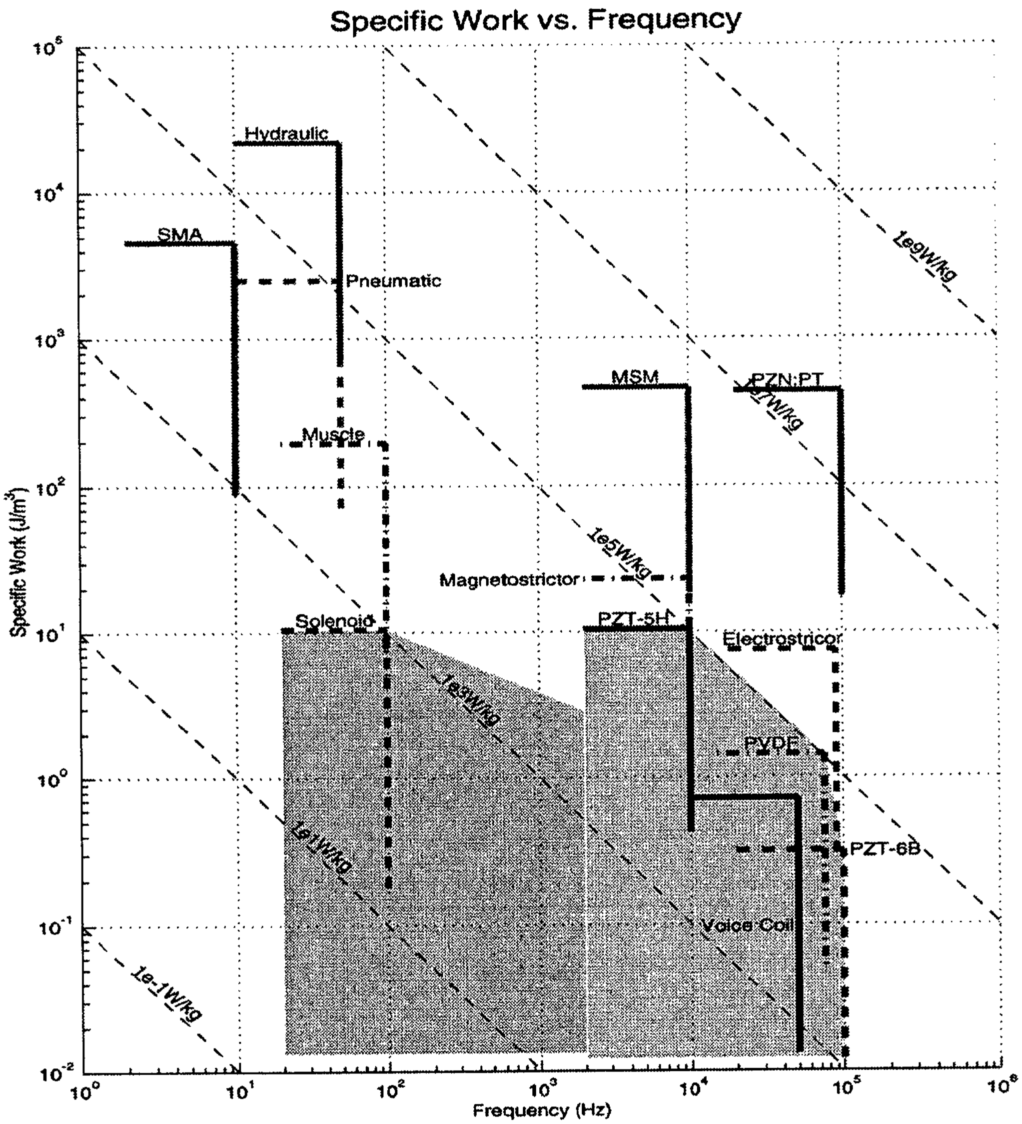
Stress vs. Strain



DARPA/DSO DSRC Study on Uninhabited Vehicles - Actuation Technologies

Specific Work vs. Frequency
Power/Mass Comparison



DARPA/DSO DSRC Study on Uninhabited Vehicles - Actuation Technologies

Implementation Comparison

Implementation	Achieved Power/Mass (W/kg)	Theoretical Limit (W/kg)	Ashby's Limits (W/kg)
Hydraulic rotary arm actuator	600	200,000	25,000
Pneumatic servovalve	200	100,000	20,000
Mabuchi Brush DC Motor	160	35,000	260
Kannan Brushless DC Motor	17	35,000	260
McGill/MIT EM Motor	200	35,000	260
Kumada Standing-Wave US Motor	50	100,000	212,000
Shinsei US Motor	16	100,000	212,000
8-mm ring prototype US	108	100,000	212,000
Magnetoelastic Wave Motor	5	150,000	80,000
NiTi SMA	6	50,000	15,000
Human Biceps	50	15,000	450

DARPA/DSO DSRC Study on
Uninhabited Vehicles - Actuation Technologies

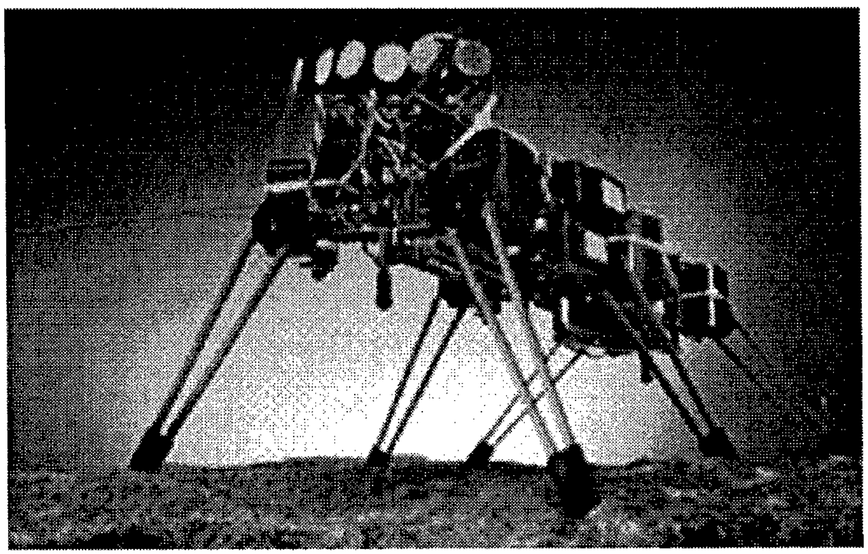
Comparison: Ultrasonic vs. Electromagnetic

Type	Model/ Description	Maker	Stall Torque [Ncm]	Max. Speed [rpm]	Peak Eff. [%]	Mass [g]	Torque Density [Ncm/kg]	Power Density [W/kg]
EM	1319E003S/ Brush DC	Micro Mo	0.33	13,500	71	11.2	29	104
EM	FK-280-2865/ Brush DC	Mabuchi	1.52	14,500	53	36	42	160
EM	Brush DC	Maxon	1.27	5,200	70	38	33	45
EM	Brushless DC	Aeroflex	0.98	4,000	20	256	3.8	4.0
EM	Brushless DC	Kannan	8	5,000	80	600	13	17
US	Standing wave, twist-coupler	Kumada	133	120	80	150	887	~ 50
US	USR60, disk-type	Shinsei	62	105	23	230	270	16
US	EF 300/2.8L, ring-type	Canon	16	40	30	45	356	~ 5
US	Two-sided prototype	MIT	(170)	(90)	(16)	330	(520)	(15)
US	8-mm ring prototype	MIT	0.054	1,750	n/a	0.26	210	108

DARPA/DSO DSRC Study on Uninhabited Vehicles - Actuation Technologies

Land Based Rovers

Mass Breakdown of Genghis Robot



Component	% of Mass	Mass(kg)
Structure	17	.44
Electronics	24	.62
Actuators	21	.55
Power Source	7	.18
Payload	31	.81
Total Mass:		**2.6 kg**

DARPA/DSO DSRC Study on Uninhabited Vehicles - Actuation Technologies

Point-Man Mission
Description

Mission[1]

– To transport an explosive payload to an occupied structure

System Requirements

– Duration	4 hrs (1 hr at peak power output)
– Mass	15 kg
– Top Speed	1 m/s (10 m/s desired)
– Maneuverability[2]	1 - 10 m/s^2
– Terrain	Rough (stairs)
– Max Power Required[3]	150 - 1500 W

1. Derived from a conversation with Eric Krotkov, TTO, DARPA
2. Maneuverability based on acceleration of robot from 0 to max speed in 1 second
3. Power required to move robot up vertical incline at max speed

Micro UAV
Actuator Mass

- Requirements Derived from Lincoln Laboratory Report

	Power	Mass
• Budgeted Requirements:	300 mW	3.5 mg
• Actuator Mass Required		
– electromagnetic (1 μNm)	150 mg	
– electrostatic	20 mg	
– piezoelectric	0.1 mg	

- Actuator is only small part of mass and power budget of flight control system - electronics taks up most of the budget
- The key challenge is packaging and integration
- main motor for propulsion is better candidate for advanced motor technology
  - It is ~25% of system mass and its efficiency dictates duration

Breguet equation - define relationships among

$$\frac{final\ weight}{initial\ weight} = e^{-c_j R / VE} < 1$$

propulsive efficiency (cj is lb fuel/lb thrust/hour)
aerodynamic efficiency (E = L/D)
range (R)
airspeed (V)

note - for endurance time replace R/V with loiter time

structures does not appear explicitly

Aerodynamic efficiency

...how many ways can an aerodynamicist cause trouble for the structures guy?

$$\left(\frac{L}{D}\right)_{\max} = \frac{b}{2}\sqrt{\frac{\pi e}{S_{wet} C_f}}$$

e=spanwise load efficiency (0.75)

Cf=skin friction coefficient

Swet=surface area

b=wing span

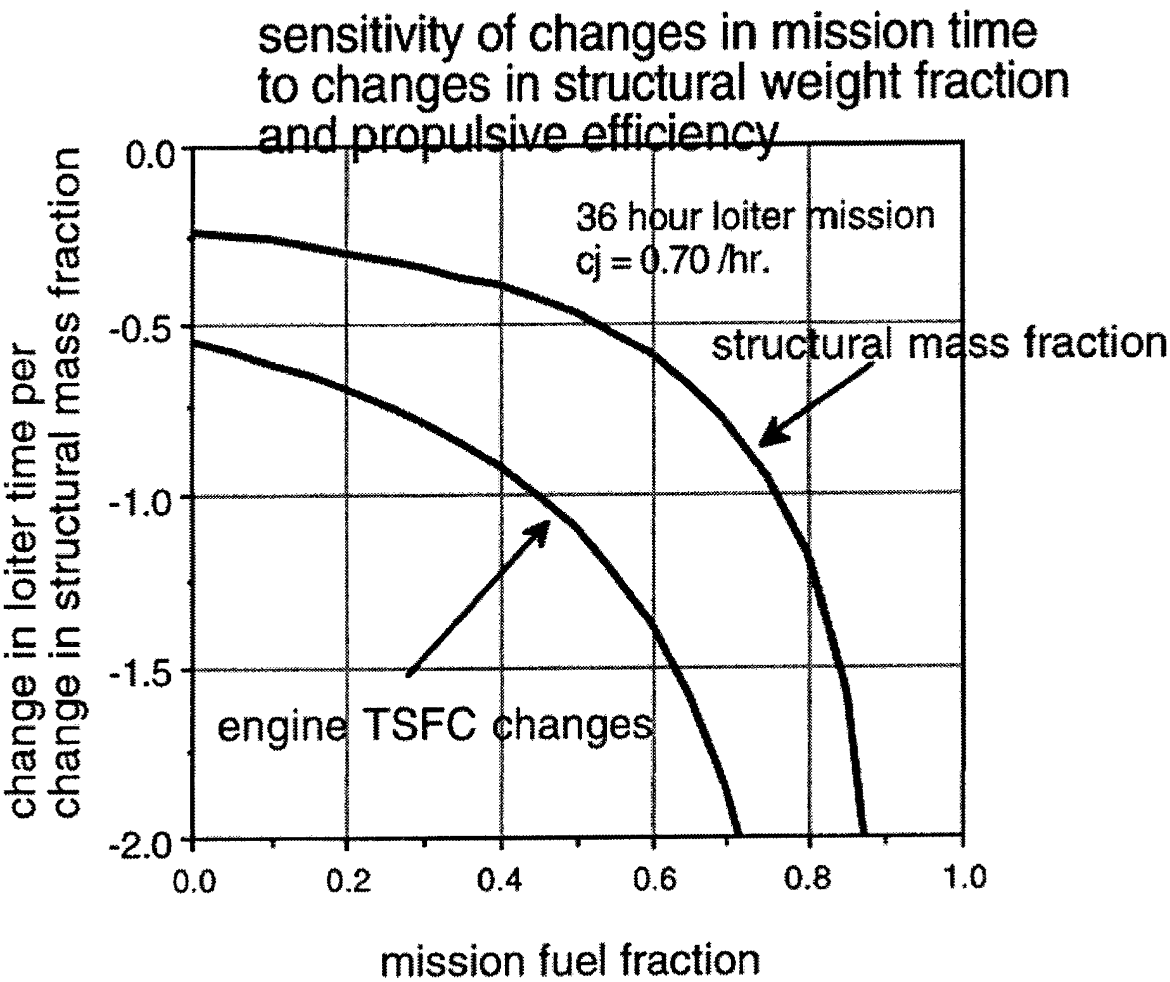
We know that a small empty weight fraction is important, but tell me again

$$W_{TO} = W_{fuel} + W_{payload} + W_{structure} + W_{systems} + W_{propulsion}$$

$$\frac{final\ weight}{initial\ weight} = e^{-{c_j R}/{VE}} < 1$$

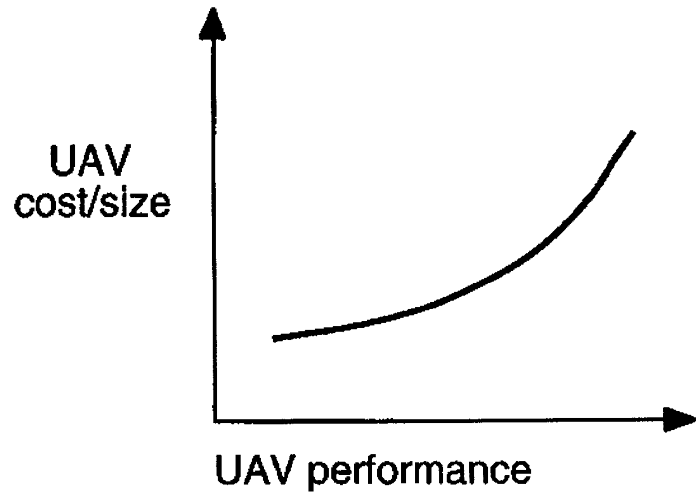
$$W_{TO} = e^{{c_j R}/{VE}} \left(W_{payload} + W_{structure} + W_{systems} + W_{propulsion} \right)$$

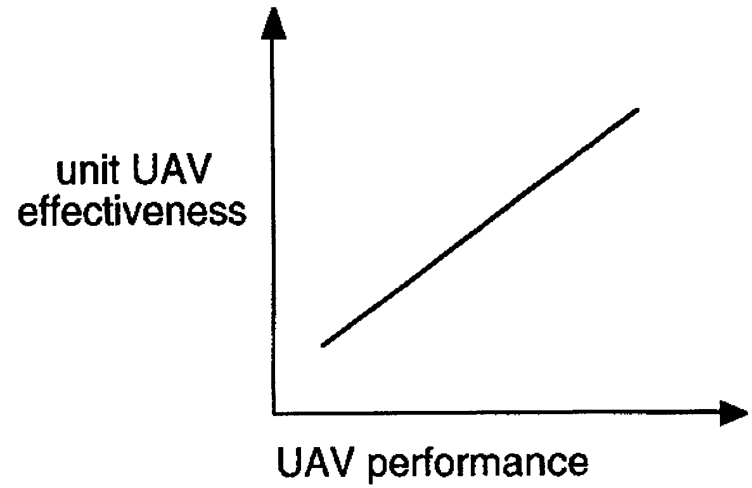
Example

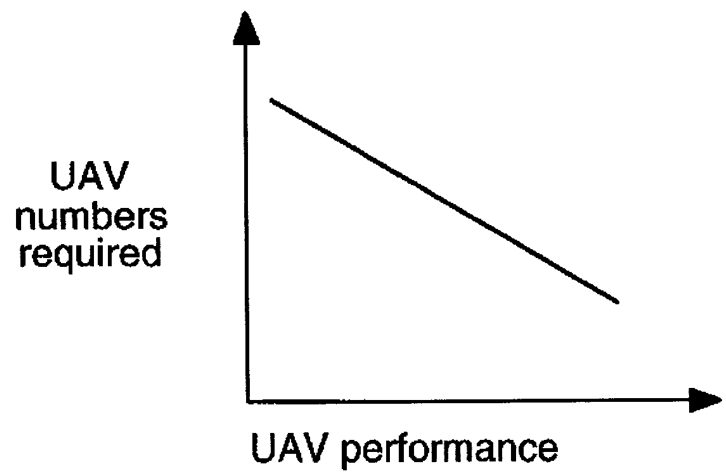


conclusion — structures and engine improvements are most valuable when the loiter time is extreme

Performance and complexity issues







UNINHABITED VEHICLES

Study Organizer: A. Evans

Wednesday, July 16, 1997

8:00 a.m.	**Objectives and Structure of Study** Anthony Evans (DSRC) Steve Wax (DARPA)
8:30 a.m.	**Summary of Uninhabited Vehicle Missions and Systems** Steve Wax (DARPA)
9:00 a.m.	**Next Generation Systems** H. Wadley (DSRC), Milan Mrksich (DSRC)
10:15.m.	**Power and Propulsion** A. Epstein (MIT), Jim Williams (DSRC)
Noon	**Lunch**
1:00 p.m.	**Actuation Technologies** E. Cross (DSRC), N. Hagood (MIT)
3:00 p.m.	**Break**
3:15 p.m.	**Minimum Weight, Affordable Structures** J. Hutchinson (DSRC), T. Weisshaar (Purdue), B. Budiansky (DSRC)
5:15 p.m.	**Ajourn for the day**

Thursday, July 17, 1997

8:00 a.m.	**Technology Priorities and Integration Issues** A. Evans (DSRC) J. Williams (DSRC), S. Wax (DARPA)
Noon	**Adjourn**

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July 16, 1997

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MULTIFUNCTIONAL DYNAMIC MATERIALS SYSTEMS: A MICRO-C4ISR SENSOR

A. Heuer, E. Hu, R. A. Reynolds, J. E. Bowers, R. M. Osgood, H. Wadley

EXECUTIVE SUMMARY

Objectives

To study the nature of, rationale for, and means of creating Multifunctional Dynamic Materials Systems (MDMS) devices that perform at least three unrelated systems functions, and to assess their role in DoD applications.

DoD Relevance

Many current and emerging DoD applications require systems' functions that are not now available at the single chip level, and furthermore are limited by power, weight, or real estate. In such a case, integration, particularly heterointegration at the materials level and fabrication of an MDMS device, may be the only pathway to achieve the system function. Challenges exist in the design, processing, packaging and reliability of such MDMS devices, as well as in deciding the level of integration necessary and appropriate for the system performance, and in defining the benefits in costs, weight, and power to achieve the resulting device performance.

We selected the micro-UAV platform as a useful framework for defining parameters of a MDMS device for airborne surveillance -- a micro-C4ISR sensor. In particular, the strong constraints of the power budget and considerations of weight and real estate of micro-UAVs mandate an integrated design of electronic components. A real-world need exists for highly integrated multifunctional chips for C4ISR sensing. However, the micro-C4ISR sensor we envisage will have applicability far beyond the micro-UAV platform. It can be used, for example, with any land-based or airborne UV, and for any manned operations where weight or power considerations are important.

Summary of Scientific & Technical Issues

MDMS devices are defined to perform at least three systems functions to achieve benefits in reduced weight, power, and cost. For this to be possible, heterointegration at the materials level is an absolute necessity. During several workshops over the course of the Study, an advanced sensor for airborne surveillance on a micro-UAV platform became the framework for specifying a particular MDMS device - in essence, a micro-C4ISR sensor. The micro-UAV vehicle provides a "real-world" application where constraints of weight, real estate, and power are particularly severe - the total weight, for example, is only 50 gm. (See Table I). The data in Table I are from the current Lincoln Labs micro-UAV effort: given the payload and *currently available* technology, they expect to be able to provide visible images at a data rate of 0.5 frames/sec.

Table I - Lincoln Labs Current Micro-UAV Specifications

Wing Span	15 cm (6")
Airframe Communications	6 gm
Flight Control	3 gm
Propulsion System	36 gm
Payload	
Communications	3 gm
Sensor	2 gm
Total weight	50 gm

The Study focused on a micro-C4ISR sensor that would provide multi-spectral imaging (a Multispectral Imaging or MuSIC Chip). The challenges in such a micro-C4ISR sensor are formidable, even at the level of the individual components. The real benefits of the MuSIC chip lies in the ability to design and fabricate an integrated chip with close attention to power budgets, device matching and device compatability. We briefly summarize some of the system tradeoffs and issues that must be addressed in the design of such a C4ISR sensor. The intention is to suggest the range of device, technology and materials choices that are to be made, and to examine whether MDMS represents an achievable and flexible approach in meeting the range of specifications.

A. Systems Level Issues

1. Communications from the micro-C4ISR chip to some control center are naturally critical. The communications can be either direct or via a relay (satellite) to a ground-based unit that may be either man-portable, stationary or vehicular. The communications may either be line-of-sight (LOS) or non line-of-sight (NLOS). There may be greater flexibility associated with NLOS communications, but there are a number of optimization issues associated with the power, frequency of transmission, antenna geometry, etc., that depend on this LOS/NLOS option. As a defining constraint for this particular Study, we chose to focus on LOS communications.

The choice of communications frequency is important. Current implementations of electronics for a micro-UAV utilize microwave frequencies, although some consideration had been given to the use of an optical link both at Hughes and at Lincoln Laboratories. A researcher at Lincoln Labs believed that better signal-to-noise could be achieved with microwave, for the same number of incident Watts, and that communications at optical frequencies would require 'exquisitely narrow' beams and pointing accuracy. A variety of current device technologies satisfy many of the high-speed, low power requirements of these communications electronics, although given the constraints on payload weight, there is no purely COTS approach. Further work will be needed to overcome phase noise limitations for low-power operation, and to obtain improved power-added efficiency.

The Study also revealed some very real potential advantages in utilizing communications at optical frequencies. Firstly, there is the large bandwidth available with optical transmitters and receivers. Unlike the cluttered microwave spectrum, where many applications compete for limited bandwidth, the optical spectrum has 200 Thz available. The very limited payload of a micro-UAV may severely limit the amount of data compression that can be carried out on-chip; data transmission at 100 Mbit/s is possible using optical beams. Secondly, the much shorter optical wavelengths allow much smaller antennae, and less diffraction loss (proportional to the square of the wavelength). Yet another benefit in working with optical sources is related to the issue of providing external power to the micro-UAVs,

allowing for missions of essentially unlimited duration. This will be described further in Section A.4, below.

Finally, in the choice of a communications technology, ***countermeasures*** also need to be considered. It is likely that a micro-UAV will have modest air speeds, and will thus be prone to attack. Micro-UAV countermeasures will require encoding of the control signals (to prevent hostiles taking over micro-UAV with more powerful signals). Thus, one may wish to avoid use of omni-directional transmission, as beamed transmission will be more difficult to intercept. Whether communications is carried out at microwave or optical frequencies, beam transmission requires a high altitude relay or LOS.

2. The design of the **communications antenna** is strongly linked to the choice of communications frequency, and the desired range of communications. Several point designs were presented that suggest suitable communication antenna options are feasible; however, none has been reduced to practice in the laboratory. Link-budget analyses have been carried out for various antenna geometries, assuming a LOS communications path. The calculations suggest that a stub antenna operating at 3 Ghz can be designed, with a 2 km range, 0.5 gms weight and 10 mW power. The calculations also presume no "covertness", i.e. no antijam or encryption which would increase platform power needs and reduce effective data rates. One approach to increasing the comm-link range, while remaining within a micro-UAV operational concept envelope, is to exploit directional "smart" or ESA (electronically scanned array) antennae. Point design calculations suggest that an ESA with cone coverage of 120° could extend the range to 10 km, but with weight (several grams) and power penalties for on-board processing and INS (inertial navigation system) requirements that may be unacceptable. Lincoln Labs has also designed a simple 0. 75 cm dipole antenna, operating at 21 Ghz, integrated into the micro-UAV tail assembly. There seems to be progress and potential in compact, low weight antennae, and radically different approaches, such as dynamically reconfigurable RF-MEMS antenna systems , may provide the real breakthroughs.

3. A related issue for antennae is the nature of the **guidance system**. Current commercial GPS is far from suitable for micro-UAV applications; antennae weigh 20-40 grams, and chip sets require ~ 0.5 W power. There is active COTS development of GPS on a single chip, and Lincoln Labs is developing an extremely light-weight GPS antenna, 0.5-1.0 gram, based on a specially developed high dielectric material. There are some limitations of GPS availability, and sub-one meter resolutions may depend on long measurement times; therefore many potential missions of a micro-C4ISR sensor may require a combination of GPS and inertial navigation in a single integrated device. Aside from adding to the device complexity, provision of an elaborate guidance system will add to both size and weight.

4. **On Chip Power** is a critical concern for the micro-UAV as a whole, as well as for the C4ISR sensor chip. These applications will provide a demanding challenge for efficient, integrable, compact battery systems. A number of innovative powering concepts arose through the discussions of this Study. One approach involves the use of *optical powering*. One reason that the payload budget for a micro-UAV is so limited is that much of the weight is allocated to the fuel or battery. Even with this large allocation, the flight duration is limited to 1 hour or less in current embodiments. The basic problem is that batteries have relatively high mass to energy ratio, but the ratio scales to zero for small power requirements. Fuel has a much higher mass to energy ratio, but there is a minimum weight allocation required for the fuel cell or engine. Hence, these curves always cross and batteries are optimum for short missions, while fuel is optimum for long missions. External powering provides an alternative that reduces the weight and also allows for unlimited duration missions. The curve for optical powering is shown in Figure 1 and it tends to fall below the other two at all mission durations. The reason for this can be seen in Table II, where the mass to energy ratio for a wide variety of materials is shown. The ratio for optical powering goes to zero as the mission duration increases. The calculation shown assumes a 100 hour mission and a weight of 1 gram, approximately 10 times the weight of the required optical detector. Even with these conservative numbers, the mass to energy ratio is still 10 times better than the best demonstrated alternative.

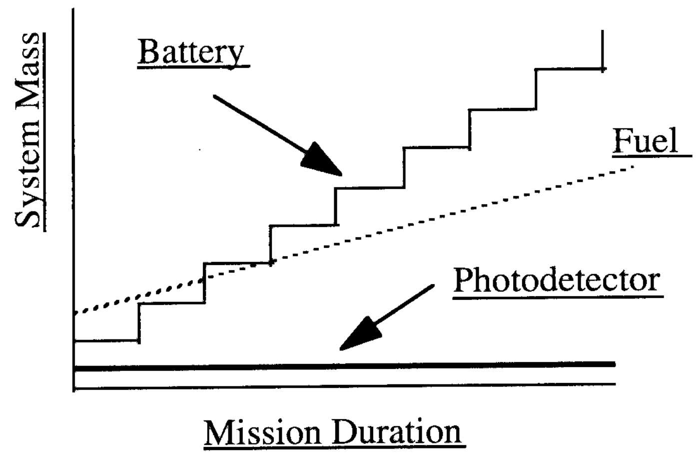


Figure 1

Table II - Fuel Consumption Comparison

Structure	Consumption, kg/kwh
Small diesel (7.5 kW)	0.23
Light helicoptor gas turbine (500 kW)	0.38
Small H_2 fuel cell (0.1-1 kwe) 45% efficient	0.06
$LiSO_2$ Battery (current SOA)	5.7
Photodetector	10^{-2} (100 hour)
	10^{-3} (1000 hour)

One of the major problems with this approach is acquisition and tracking; the UAV launcher rail provides a good initial path for locking on an optical beam. Can optics track the UAV over a distance of 10 km? Presently, optical tracking has been investigated for distances of 50,000 km for satellite-to-satellite transmissions by Lincoln Labs. They have demonstrated acquisition of a long range target with just 5 pW of received power. The transmitted power would be typically 1 W. The acquisition and tracking problems are similar to other potential Air Force programs, such as the Illuminator program proposed by Hughes, where a kW Yb:YAG laser would acquire, track and destroy an incoming missile. The power requirements for the UAV are a very small fraction of this, namely 1W or less.

Recent advances in solid state lasers make this approach more attractive. Diode pumped solid state lasers produce kilowatts at a variety of wavelengths. Diode pumped fiber lasers with 65 W output from a single mode fiber were recently demonstrated. These are compact, robust sources, but the important point is that they would be on the ground in the base station rather than located on the critical UAV component.

5. **Imaging Technologies.** From early on in the problem-definition process, it was determined that we wanted to carry out imaging at several wavelengths. Driven by the commercial sector, the development of on-chip imaging capability in the visible wavelength range is proceeding rapidly. With regard to infrared (IR) imaging, several technological challenges exist for light-weight low-power IR cameras that one might want to use in a micro-C4ISR sensor. To be useful for this application, the IR camera needs to provide a high resolution thermal image without exceeding weight and volume constraints. The current systems weigh 70 to 80 lbs. and require 100 watts of power, primarily for their cooling systems. Development programs aim to lower the weight to 7 lbs and reduce the power requirement to 8 watts. Clearly, a micro-UAV or other platform that has a total payload budget of 5 gm. requires either much more development or a breakthrough if it is to incorporate an IR imager.

Infrared imaging technologies based on HgCdTe, InSb and PtSi have to be cooled well below room temperature to achieve adequate resolution. The weight associated with any cooler that can accomplish this exceeds the payload budget; the most compact IR camera now available weighs 15 grams, compared to 2 grams for a visible camera. Uncooled infrared detectors with adequate spatial resolution are not currently available.

To achieve 0.1m resolution, a 1024 by 1024 element array is needed. Only PtSi infrared cameras have been successfully fabricated with such large arrays, and incorporate a monolithic CCD readout, allowing reduced pixel size. However, PtSi-CCD arrays need to be cooled to at least 80K to achieve sufficient sensitivity. HgCdTe and InSb arrays have higher sensitivity, which can be traded off for higher temperature operation, but have been limited to smaller array configurations. A 640 by 480 HgCdTe array has been demonstrated.

It is clear that new technology is needed for IR imaging within the micro-C4ISR sensor weight constraints. Camera operation in the near-infrared region (1.5 µm) , might involve thermoelectric cooling, wavelength selective optical cavities and monolithic silicon microlenses. Imaginative isothermal but ambient temperature solutions via microbollometers or pyroelectric materials, where temperature stabilization is achieved without a large weight penalty, need also to be investigated.

6. **Signal processing** of video imaging at the microscale is also difficult. The Study heard an extensive discussion of the various tradeoffs and requirements needed to preprocess the video images prior to transmission to the base station. In some ways, this problem is the very opposite of the usual video compression issue present in normal commercial applications. In that case, the signal processing is done at a very large and well-equipped studio, where power and size are not the issue, while the receiving station is in fact the point at which size and cost are at a premium. The conclusion of the Study group was that because of this, the signal compression should not be done if possible and that it was best to either do some modest custom compression or to carry out direct broadcast.

B. Techniques for Integration

During the Study several different approaches to integration were described, ranging from those which are immediately applicable to techniques requiring substantial research before they can be implemented in manufacturing. The techniques include multichip modules (MCMs), bump bonding, lift-off, wafer fusion, and heterogeneous growth. The Study found that there were many new and important developments in these areas which should allow integration of an entire subsystem for a platform such as a micro-C4ISR sensor.

1. **MCMs**: A series of chips may be mounted in a compact assembly containing its own wiring, what is termed a multichip module. In the Study, a graphic illustration was shown of the importance of this hybrid-mounting scheme; the Mayo Clinic showed that even a modest level of integration could reduce the weight of a GPS unit by a factor of 5. With regard to future technologies in this area, a revolutionary approach to this mounting scheme was shown in results from Lincoln Laboratory. A very precise MCM could be

formed on a silicon chip by a series of planar processing techniques, each done in conjunction with chemo-mechanical planarization after each step of the process.

2. **Bump Bonding**: Bump bonding allows a chip to be bonded to an electrically active substrate via a regular array of small indium solder bumps mounted on both the chip and the substrate. The attractive feature of the technique is that the bumps act to self-align the two structures, to bond them together, and to electrically connect them. This technique has been used in many development and commercial products, including several different focal plane array technologies, where the bonding allows integration of the detector array with a CMOS processing chip. This approach is both practical and relatively easily implemented; it does suffer from the fact that the electrical connection is rather limited in geometry and subject to problems at higher temperatures. One important area of research in this area is to reduce the physical size of the solder bump to smaller dimensions and smaller pitch. This development would permit finer features to be used on an array chip. These finer features would be important, for example, in the case of reduced pixel sizes on a focal-plane array.

3. **Lift Off**: In this approach, a thin layer of epitaxial crystal is released from the bulk crystal on which it is grown. The method of release is typically done by selective etching of a sacrificial layer having a chemistry distinct from that of the underlying substrate. The technique has been extensively applied to heterointegration of semiconductor materials and has been used to place, for example, an MBE-grown GaAs HBT (Heterojunction Bipolar Transistor) or solar cell on a silicon wafer. In its usual form, the technique does not allow for electrical contact between the lifted-off device and the substrate. Recently, this technique has been applied to the integration of thin oxide layers on the surface of a semiconductor; the technique is important since it allows the integration of epitaxial layers of extremely diverse materials types.

4. **Wafer Fusion**: Wafer fusion has the same general objective as lift off; however, in this case the substrate and overlayer are atomically fused together by the application of heat and pressure. Typically this process is accomplished by bonding two wafers and then using selective etching to release a thin film from the upper layer. This process does not require lattice matching between the two surfaces. Since the contact between the two wafers involves fusing of the bare materials, the interface is transparent to light (as in lift off) and to flow of electrons. Recently the interface has been shown to be of sufficiently high quality that it can base minority carriers and has been used to form a p-n junction. The central research issues in this case are to understand in greater detail the materials physics of the fusion process, to extend the range of materials for which it may be used (at present, most of the results have been on materials containing some indium content) and to understand in detail the thermomechanical issues involved in the fusion.

5. **Heterogrowth**: Obviously from the point of large-scale manufacturing, the most economical approach to heterointegration would be to grow all materials on the underlying substrate, perhaps in the form of sequential layers. Unfortunately, this capability has been an elusive goal since many of the early examples were notably unsuccessful. As a case in point, the growth of GaAs on Si was unsuccessful due to the presence of defects in the ovelayer. Recently, however, as a result of careful and long-term attention to this form of growth, there have been some important successes. For example, the growth of HgCdTe on Si has been done successfully and now forms the basis of one important focal plane technology. In addition, the Study found that important progress has been made in the area of growing GaAs on Si through a very new approach to the problem. In this case, a group at MIT has shown that by careful attention to compositional variation and temperature during growth, graded Si:Ge can be used to form a high quality layer of epitaxial Ge on Si. High quality GaAs can then be grown on the Ge layer.

6. **Novel Growth Technologies**: The Study also considered a number of new and relatively unexplored areas of integration between very diverse materials. For example, there are a number of new techniques being explored for the growth of materials on flexible

substrates. While the resulting material is certainly imperfect, it is adequate for many forms of device applications. Growth on flexible substrates would have considerable utility for use on ultrasmall platforms. An example of this approach for a multifunctional wingskin that incorporates a thin film photovoltaic and a rechargeable thin film battery is discussed in an Appendix.

Conclusions and Observations

A micro-C4ISR sensor for multispectral imaging - a MuSIC chip - can serve a host of DoD applications that require airborne or other surveillance and reconnaissance operations. Because of the limitations of weight and payload dictated by the systems specifications, multifunctional integration at the chip level is critical to the successful realization of this vision. Fortunately, a number of different integration technologies are currently available or under development, which should enable manufacture of MDMS devices. A number of those technologies have been catalyzed by commericial device and circuit needs, although there are key technology areas which do not have drivers in the civilian sector. In particular, light-weight, low-power integrated IR imagers provide challenging technological barriers, in large part because of the issues associated with cooled operation. A means of integrating effective cooling mechanisms on-chip via the MDMS approach would represent a major advance for this technology. The choice of particular materials to be integrated for a given micro-C4ISR sensor would be dictated by particular systems needs and technology choices. Those choices should make a selection between LOS versus NLOS imaging, microwave versus optical wavelength communications, and particular antenna configurations. Trade-offs between range versus accuracy must be considered, as well as the trade-offs between power limitations and the degree of on-chip signal handling that is to be carried out. Those assessments will determine the particular optimal materials to be brought together within an MDMS device, and consequently, the particular integration technology to be used, given the thermal budgets and other limitations set by an integrated MDMS process. With the component technologies in place, exercised within a truly demanding multi-integration application, and with the tremendous benefits to be gained from the availability of a micro-C4ISR sensor, there would be many opportunities for DARPA to catalyze important technological breakthroughs in this level of MDMS integration.

Appendix

MULTIFUNCTIONAL WINGSKINS

Secondary (rechargeable) battery technology based upon metal (e.g. Zn, Al, Li or Mg) - air anode-cathode systems can provide energy densities of 150 Wh/Kg making them potential candidates for powering microair and small land vehicles. For these applications, battery weight is a critical performance defining attribute. However, more than 70% of the battery weight is used for its external protective packing and this packing percentage increases to 85% or more as the battery size (i.e. Ah capacity) decreases.

Many of the missions scenarios envisioned for small air and land vehicles involve extended operations during which the vehicle may spend many hours, days or even weeks acting as an unattended ground sensor, interrupted by short periods of flight or locomotion for relocation or reconnaissance. A Lincoln Labs study of microair vehicles identified large reductions in the power requirements of air vehicles as their size decreased. The current MAV design calls for a 15 cm wingspan vehicle for which 4-8 W of power would be required for fixed wing flight at up to 13 m/s. But, interestingly a Lincoln Labs study reveals that a 5 cm wingspan can be flown at a similar speed using only 0.4 - 0.8W. Vehicles of this size have not been actively pursued because of concerns about payload capacity. But, small vehicles in the 5 cm size range could be of potential value if flapping flight mechanisms can be activated. Experimental studies have now shown that the flapping mode of flight is able to increase lift by 200-300% or more for some types of insects, and it becomes a more useful mechanism of flight for many urban or jungle environments.

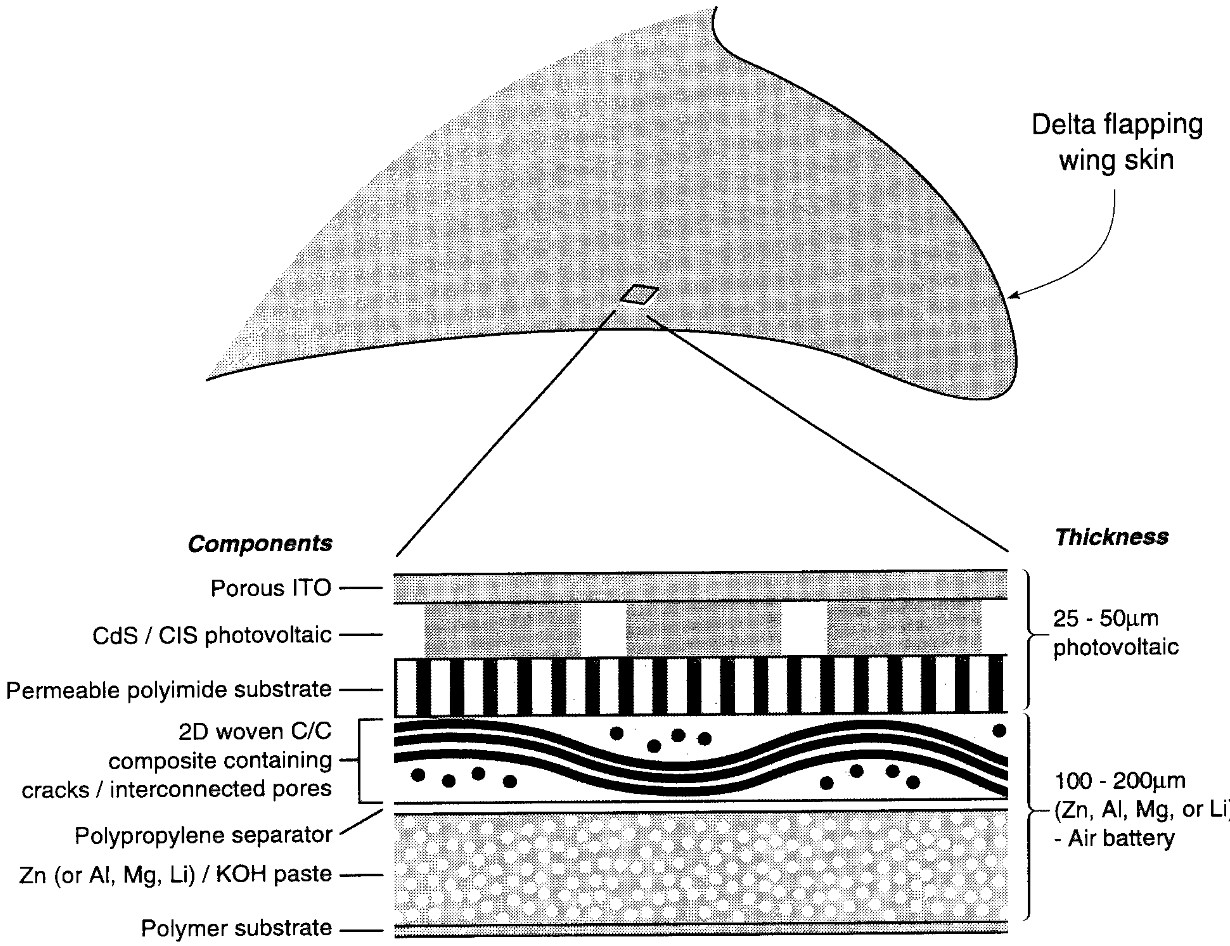
One approach to powering small vehicles is photovoltaics. A new generation of 8-9% efficient photovoltaics is being developed by ITN Energy Systems. By using 1 μm thick CdS/Cu In Se_2 films deposited on 25 μm thick flexible polyimide sheets, these new photovoltaics provide specific power outputs of 500 W/kg. Thus, the surface area of a 15 cm vehicle could obtain as much as a half of its power needs from a photovoltaic wingskin. For missions that do not require continuous flight, this raises the interesting possibility of using a combination of a metal-air rechargeable battery and a photovoltaic wingskin to provide essentially indefinite, unattended sensing capabilities.

It appears possible to go further with this concept and integrate the photovoltaic and metal-air battery as shown in Fig. 2. The notion here is to use the flexible photovoltaic as the air permeable surface of a thin film metal-air battery. This can be accomplished by depositing a porous indium tin oxide electrode and providing pathways for air diffusion through the photovoltaic structure. It is possible to then construct a multifunctional membrane that is 125-250 μm thick with sufficient flexibility to be stretched over the spars of a wing structure. The skin flexibility (i.e. stiffness) could also be tailored by replacing the noble metal catalyzed carbon-carbon composite with a 2-D woven fiber construction. In this way, it becomes possible to consider using the same "material" as a battery, a photovoltaic, an aerodynamic surface and as a load bearing structure. It may even be possible to use a part of current collection/distribution wiring (not shown in Fig 2) as an antenna for communications and global positioning. This concept of multifunctionality may have a broad impact upon numerous weight critical technologies. For example, it also appears feasible to develop a fuselage structure that functions as an airbreathing fuel used in an uninhabited land rover or underwater vehicle. The integration of a photovoltaic system could also be explored for electrolytic regeneration of hydrogen fuel to provide a means for extended, unattended operations.

Figure 2

MULTIFUNCTIONAL WINGSKIN

Light, stiff, thin film rechargeable battery, photovoltaic skin of a vehicle (e.g. next generation flapping system)



CONCEPT EXTENSIONS: Fuselage that extracts oxygen from air for an air-breathing fuel cell, regenerative fuel cell (e.g. H_2 from electrolysis / MEMS pump / buoyancy mechanism of lift).

Multifunctional Dynamic Materials Systems: A Micro-C4ISR Sensor

A.H. Heuer

E. Hu

R.A. Reynolds

J.E. Bowers

R.M. Osgood

H.N. Wadley

Multifunctional Dynamic Material Systems

Questions Addressed

- Where are there substantial benefits to be gained in **cost, weight, power**, etc. for heterointegration at the materials level?
  - Which applications?
  - What level of materials integration?
- What challenges exist in the **design, processing, packaging, and reliability** of such MDMS devices?

History of Study

March 25, 1997, SPC Corp.

Discussed various technologies where materials integration might be useful.

Conclusion: Surveillance chips; micro-UAV platform.

May 30, 1997 Stanford University

Issues viz-a-viz communications and surveillance on a micro-UAV platform discussed in depth.

Conclusion: Antenna issues solvable; 5 gm payload for micro-UAV difficult; LOS vs. non-LOS, range vs. accuracy, and GPS vs. INS need to be resolved.

June 13, 1997 Lincoln Labs

Bob Davis

IR imaging and laser communications rejected as unavailable with current technology.

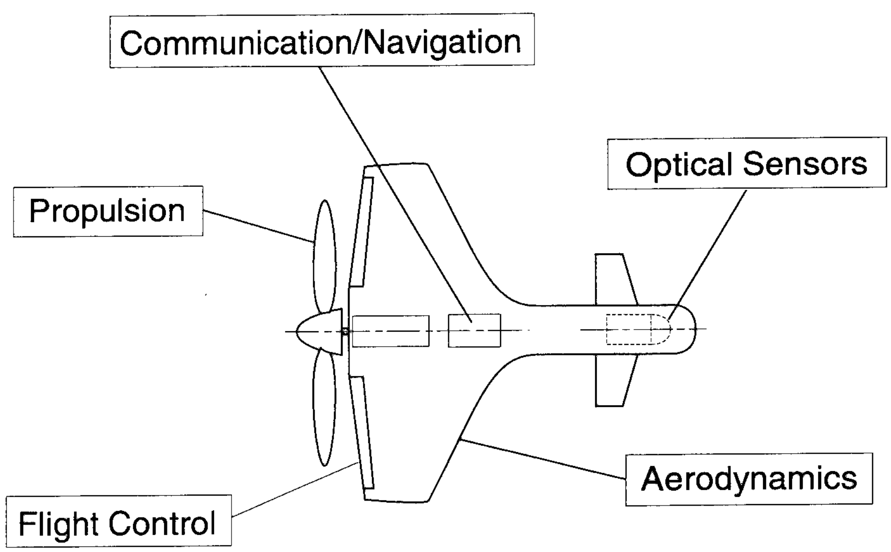
Multispectral Imaging Chip (MuSIC)

July 21-22, 1997, La Jolla

Conclusion to the Study

Current Status of Lincoln Micro-UAV Assessment

Specifications		Capability
Wingspan	15 cm (6")	Visible Images
Airframe	6 gm	0.5 Frame/sec
Flight Control	3 gm	Observations
Propulsion	36 gm	IR imaging system requires 15 gm
Payload		Laser communications
Communications	3 gm	require narrow beam
Sensor	2 gm	and high pointing accuracy



Multifunctional Dynamic Material Systems

- Micro-UAV used as framework for defining parameters of a MDMS device
  - helped to define 'real-world' need for multifunctional sensor
  - constraints of weight, real estate, and power mandate highly integrated fabrication
  - strong constraints of power budget mandate integrated design of electronic components

- Extract 'prototypical' functions:
  - will **not** address propulsion, flight control, or aerodynamics
  - focus on sensing: **surveillance via multispectral (2) imaging, and image processing**
  - focus on **line-of-site communications** (MMIC and optical)

- **Micro-C4ISR sensor**

System Options

- Communications

Control Center to Sensor	-	**LOS** NLOS LOS with relay.
Control Center	-	Man-portable land vehicle Satellite
Angle Coverage	-	Omnidirectional Highly directional
Penetration (NLOS)	-	Buildings Trees Rain Smoke

- Frequency - Microwave
  Optical

- Imaging

Spectral Range	-	Visible IR **Multispectral**
Image Processing	-	Still or Moving Images On-chip data compression

- Navigation - Inertial navigation
  GPS

System Specific Choices

- Choices of LOS/NLOS

  Communications frequencies, antenna geometries and sizes, angle of transmission, security/range.
  Study focus was LOS.

- Multispectral imaging useful, but

  - IR generally requires cooling:

  - penalty in weight and power

  - resolution required?

  - data compression is power-hungry, but some on-chip signal processing may be necessary

- How small is small enough?

  - weight, power, efficiency of operation?

Conclusion: MDMS integration is absolutely essential.

Antenna System Designs

- 3 Ghz Antenna (Hughes)

  1 mm x 5 cm, 0.5 gm, 2 Km range

- 21 Ghz Dipole Antenna (Lincoln Labs)

  0.75 cm coax integrated to tail assembly

- Light-weight GPS Antenna (Lincoln Labs)

  new high dielectric materials

  0.5 - 1.0 gm weight

Infra-red Imagers

- Severe technological challenges exist for light-weight low power IR cameras utilizing FPAs
  - Current off-the-shelf FLIR systems weigh 70–80 lbs. and run at 100 watts
  - Current development programs aim to develop 7 lb/8 watt systems. Much further development is needed.
- 1000 x 1000 pixel arrays in PtSi CCD cameras for near IR (3–5 μm). LN_2 cooling required.
- 20 μm pixel size now state-of-the-art for 640 x 480 pixel arrays in HgCdTe for mid IR (10 μm). LN_2 cooling required. The pixel size is limited by the bump bonding process. Smaller HgCdTe and InSb arrays have been built as 3-5 μm imagers.
- Could a 1.5 μm IR imager, if developed, satisfy the user community?
- Can uncooled detectors with good enough resolution be fabricated? (This needs a breakthrough!)
- Are there imaginative isothermal but ambient temperature solutions to improve resolution?

Multifunctional Chip Integration

- Absolutely needed for micro-C4ISR sensor — weight, power and volume constraints are severe
- Existence proof of benefits clear from limited work in IR imagers and GPS devices
- Some areas require sustained development
- **Material and processing challenges**
  - Incompatible processing temperatures
  - Three-dimensional stacking is often needed
  - Extreme differences in material chemistry
- **Integration technologies**
  - On-chip MCMs
  - Micro-bump bonding (needed)
  - Lift-off
  - Wafer fusion
  - Multimaterial heterogrowth

High Performance MCMs
(MIT/LL, Mayo)

OBJECTIVE

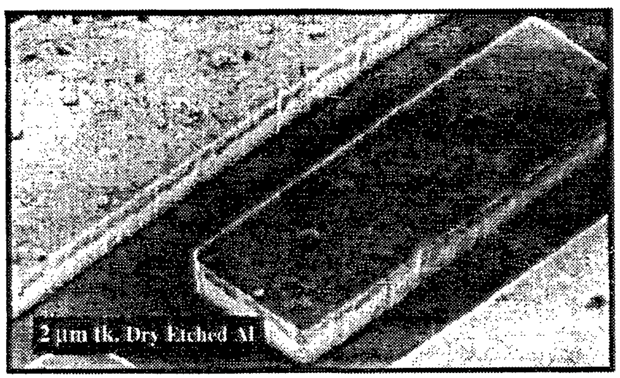
- Develop High Performance MCM Capability Through Application of Advanced Integrated Circuit Processing Techniques
- Tight Control of Process Specs Including:
  - Dielectric Thickness and Uniformity
  - Metal Thickness, Linewidth, and Sidewall
- Develop Design Rules and Provide Research Substrates To DARPA MCM User Community

APPROACH

- Start with SiO_2 Dielectric, and Aluminum Interconnect
- Incorporated Fully Planar Process Using Chemical Mechanical Planarization and Plasma Etched Metal Technologies
- Include Integrated Passive Components:
  - Capacitors and Resistors
- Increase: Dielectric Thickness, # of Power Planes, # of Interconnect Levels

ACCOMPLISHMENTS

- Program Start: 3/97
- Preliminary Test Coupon in Fabrication
- Thick Dielectric and Dry Etch Processes Demonstrated



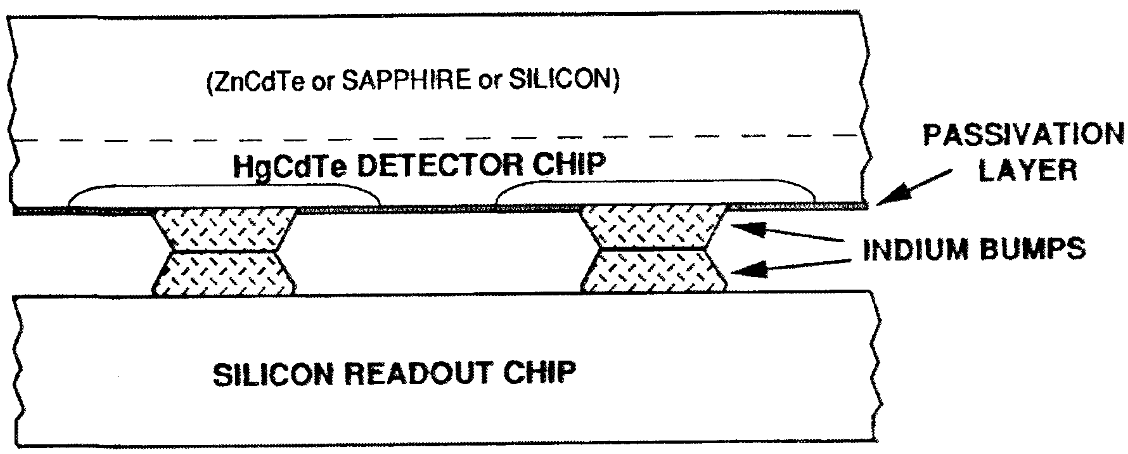
OBJECTIVE

MIT Lincoln Laboratory

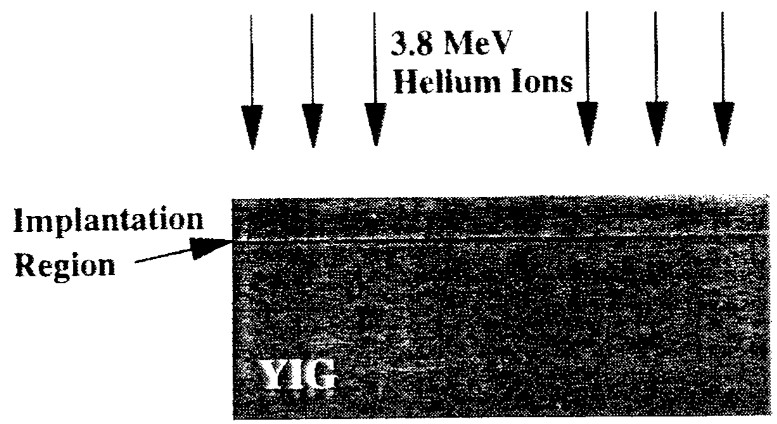
CLK 7/9/97

UNCLASSIFIED

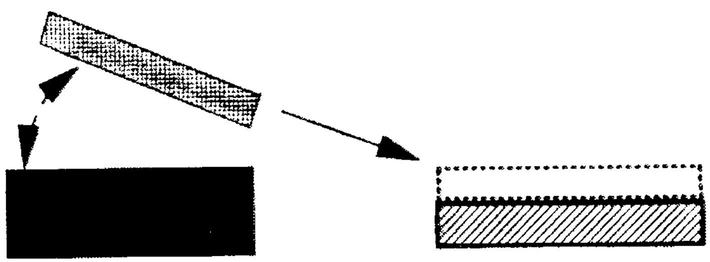
HgCdTe FOCAL PLANE ARRAY TECHNOLOGIES

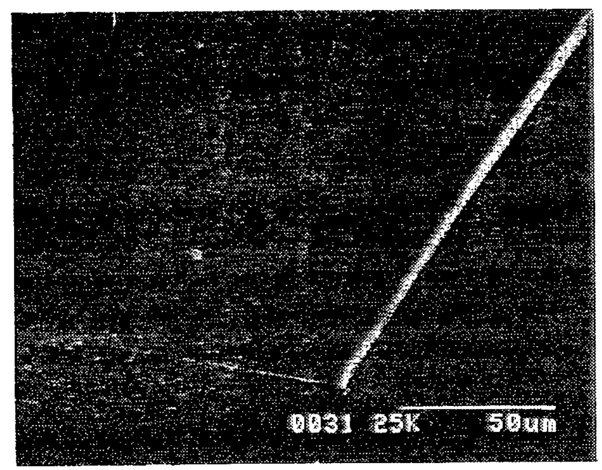


Lift-off in Metal-Oxide Systems – Crystal Ion Slicing (CIS)



- Selective Etch
- Placement on GaAs Substrate



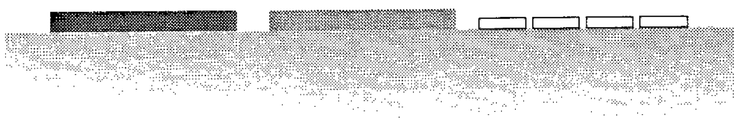


Fracture-free Liftoff Film

Columbia University

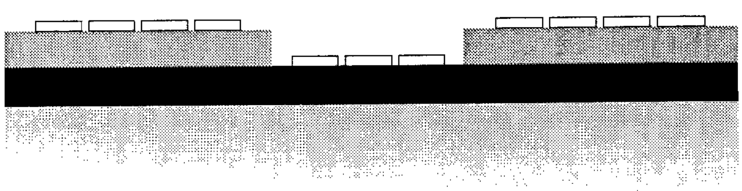
Two Approaches

Lateral Growth



CMOS Compound S.C.
Si Substrate

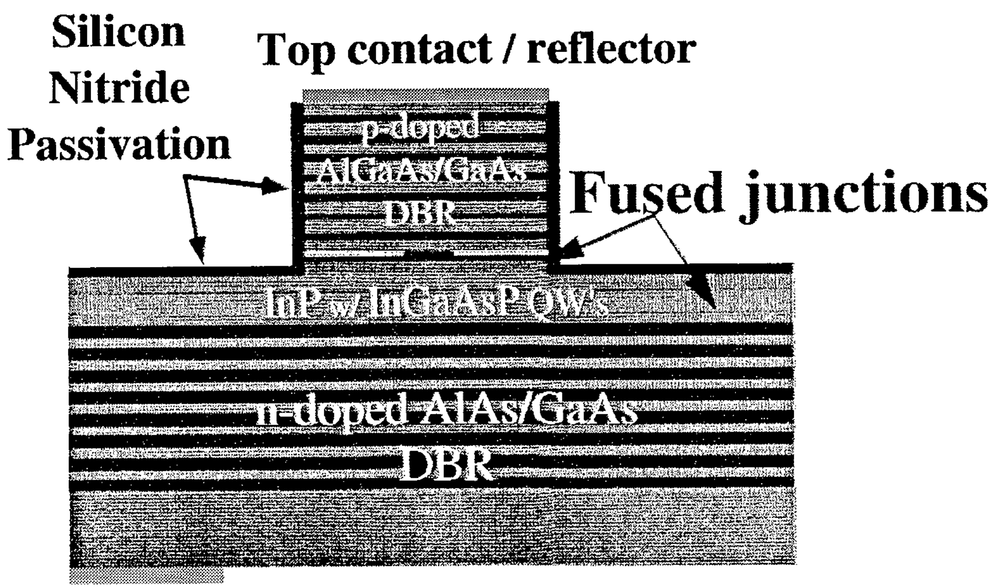
Fusion Stack

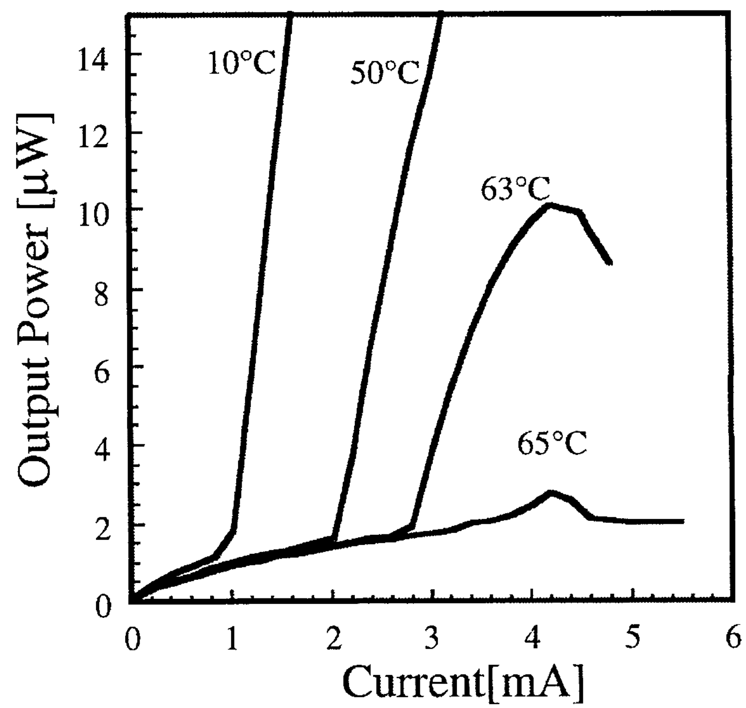


HgCdTe
GaAs
Si

- Eliminate packages–weight, volume
- Major advances in materials technology

Double-fused Vertical Cavity Laser

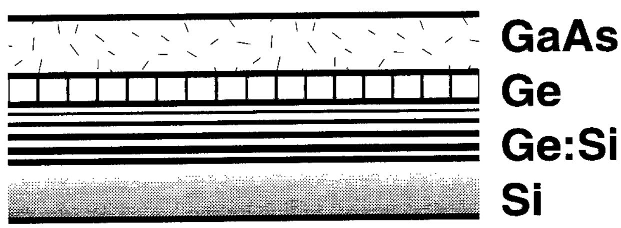




Fusion has enabled record low threshold long wavelength VCLs

Heterogrowth of Very Dissimilar Materials

- Growth allows "easy" manufacturing
- GaAs/Si has been a particular problem
- A recent materials-based solution was found by Fitzgerald at MIT



Conclusions and Observations

- Micro-C4ISR sensor requires very "heavy-duty" integration
- Multispectral imaging essential for effective airborne surveillance
- Integration techniques for multispectral imaging (a light-weight low-power MuSIC chip) does not have a civilian driver but current technology looks promising
- Light weight low-power IR imagers represent a particularly challenging technological barrier
- Unresolved issues
  - LOS vs. non-LOS
  - microwave vs. optical communications
  - range vs. accuracy
  - antennae configuration
  - level of on-chip signal handling
- Many opportunities for DARPA to provide technological breakthroughs

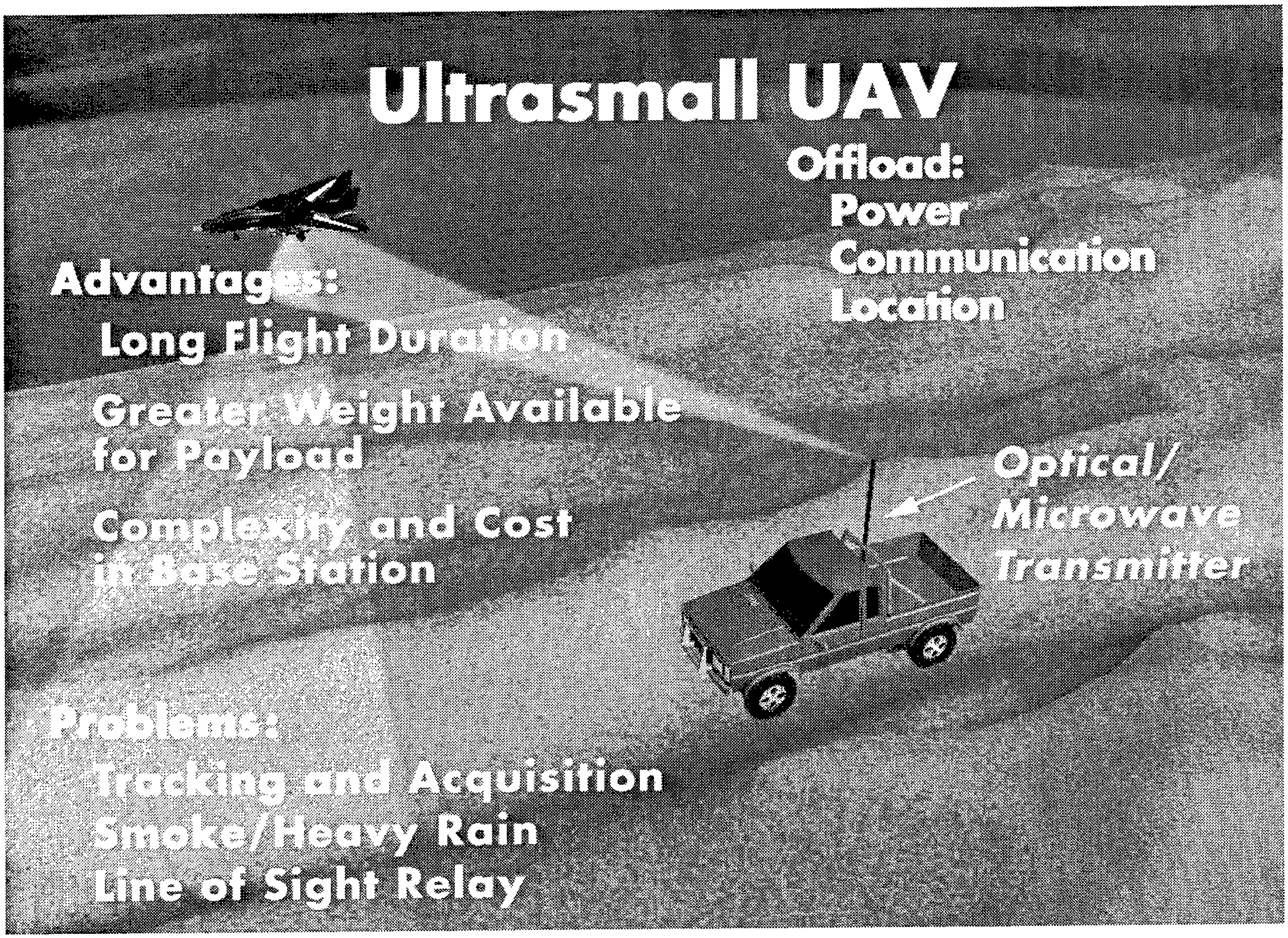
MicroUAVs

- **PROBLEM:** Difficult to scale below 1 meter due to size requirements for power source, microwave transmitters and receivers, GPS antenna and processing, image processing.
- **POTENTIAL SOLUTION:** Eliminate most functions and place in ground based station. This has several advantages:
  - Reduced weight
  - Reduced cost (expendable)
  - Reduced size (easier to carry around and more difficult to detect and shoot down).
  - More cost effective upgrades (just change the base station, not all of the birds).

Functions that could be eliminated from MicroUAV:

- GPS System
- MicroGyros
- Accelerometers
- Batteries/Fuel
- Power Transmitters

- Range from Base Station
- Range from Base Station
- Range from Base Station
  Supply power from Base
- Modulate light from Base

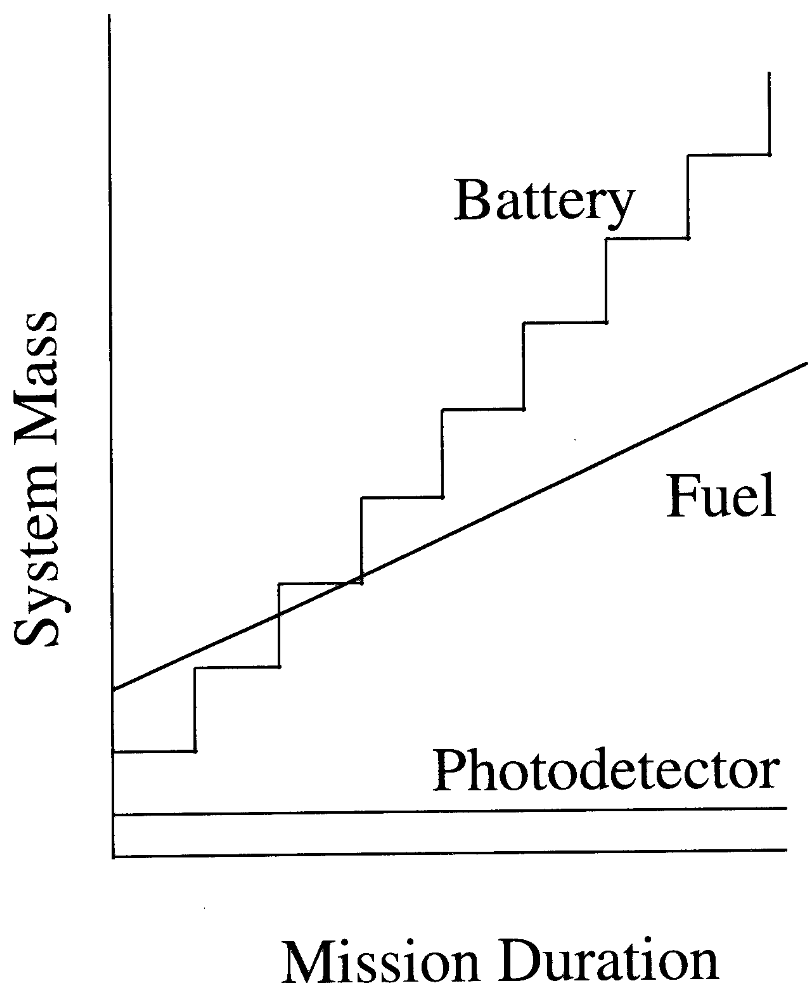

Ultrasmall UAV
Offload:
Power
Communication
Location
Advantages:
Long Flight Duration
Greater Weight Available for Payload
Complexity and Cost in Base Station
Optical/ Microwave Transmitter
Problems:
Tracking and Acquisition
Smoke/Heavy Rain
Line of Sight Relay

Useful Recent Optical Developments

- Compact, robust optical sources:
  - 50 W from a diode pumped fiber laser (this is extreme example, but 1 W high quality beam from a compact source is possible for base station)
- High data rate communications:
  - 155 Mbit/s is cheap and very sensitive
  - Optical losses of 40 dB possible
- WDM Sources/Receivers available off the shelf
  - Useful for communication to multiple UAVs

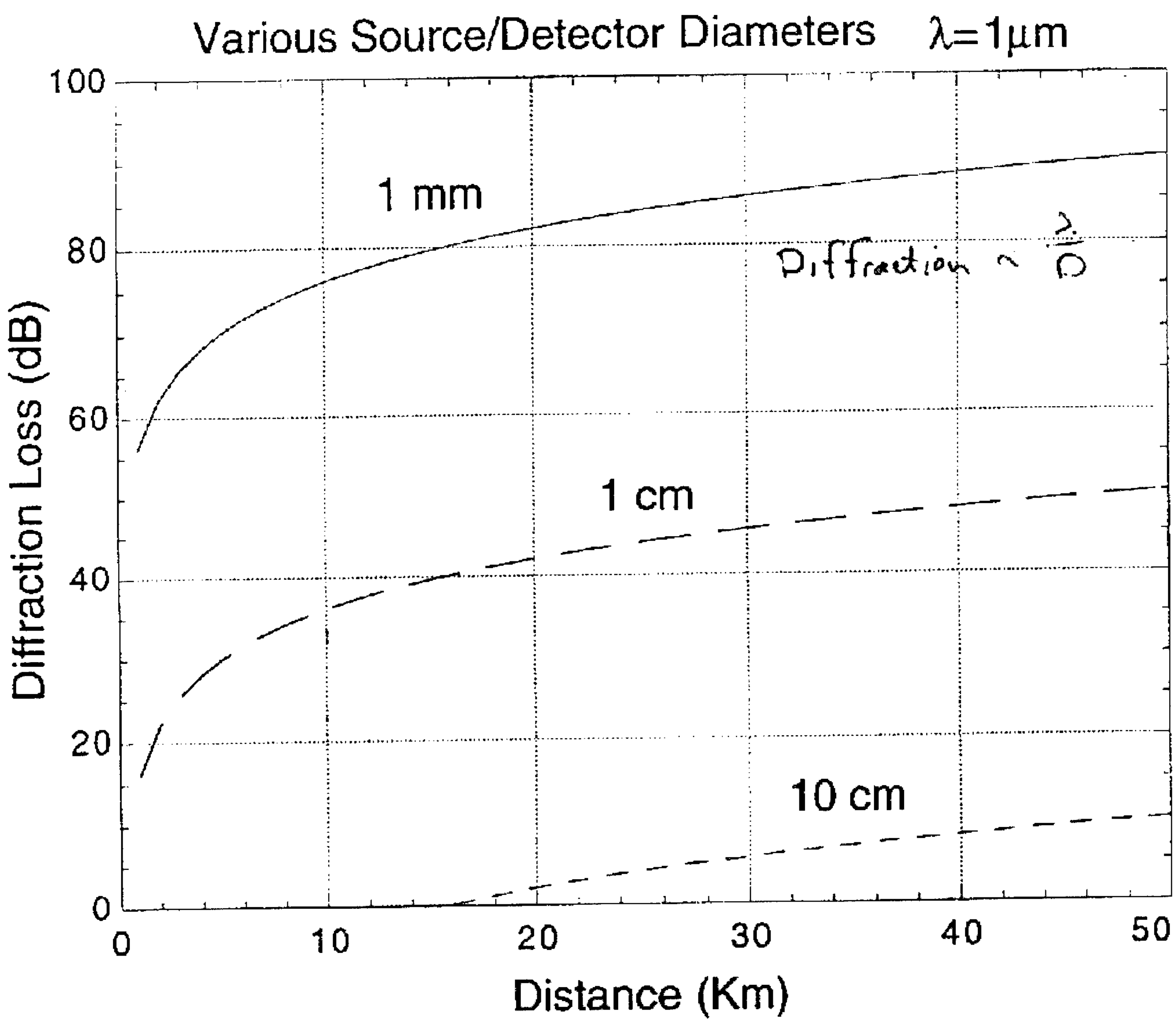
Comparison of Power Sources

- Fuel: 10 kWh/kg
- Battery: 0.5 kWh/kg
- Optical powering: 100 kWh/kg
  (100 hour)



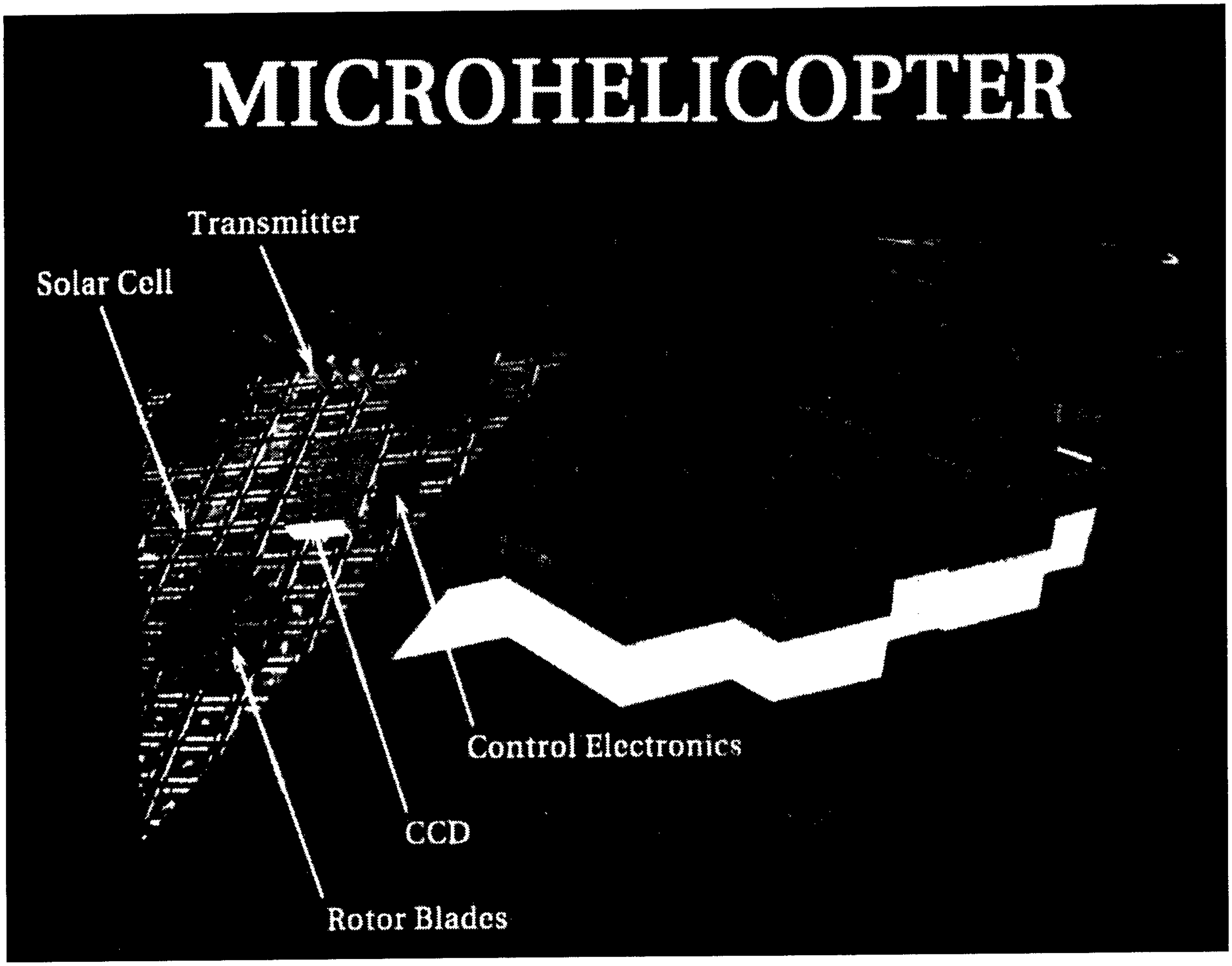
Issues

- Eye Safety: Use 1.5 μm light
- Size and robustness of source: Diode pumped solid state laser
- Use retroreflectors to eliminate laser and tracking from UAV

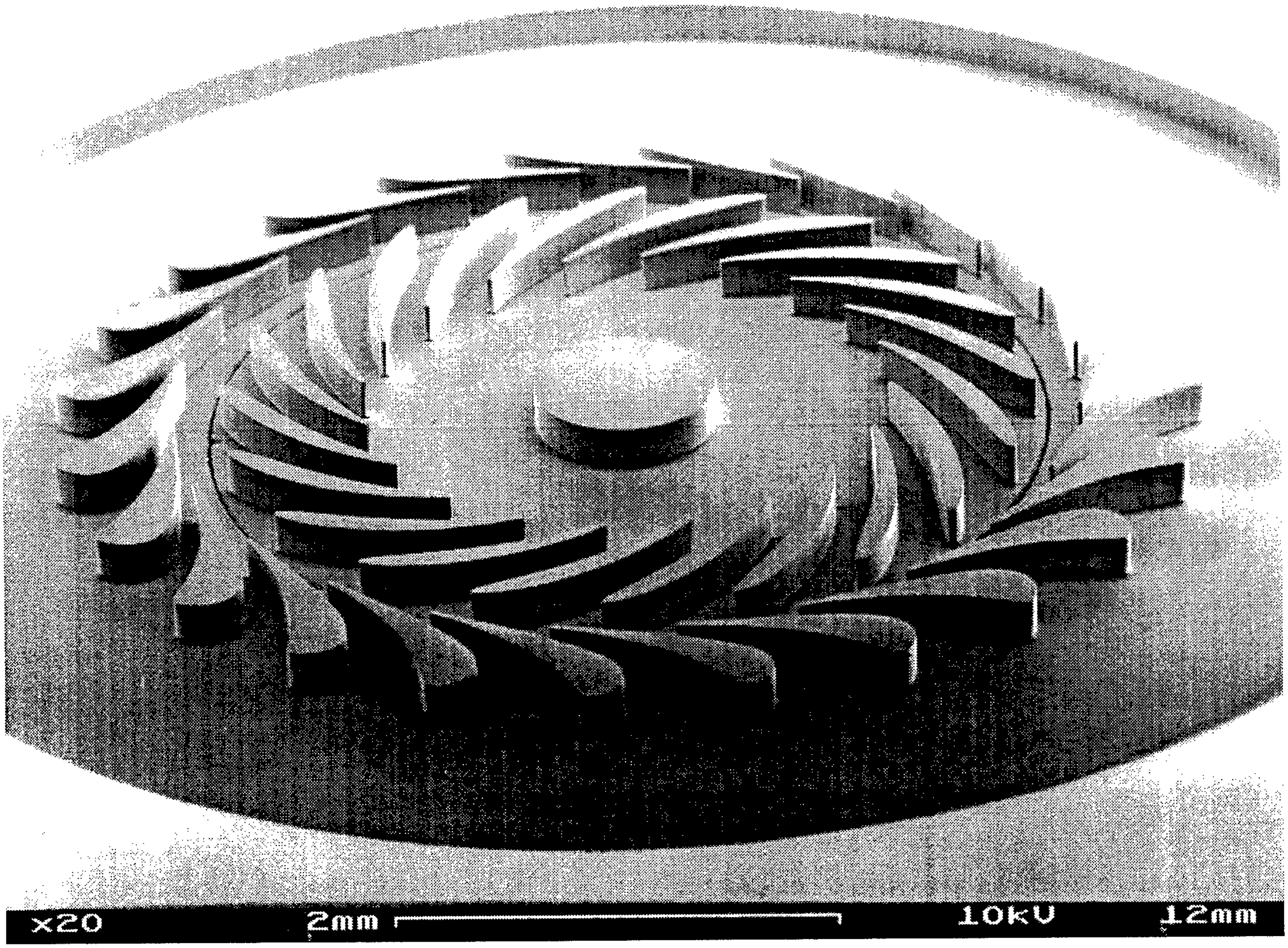

Various Source/Detector Diameters λ=1μm
Diffraction Loss (dB)
Distance (Km)
1 mm
1 cm
10 cm
Diffraction ~ $\frac{\lambda}{D}$
0
20
40
60
80
100
10
30
50

Lincoln Labs ACTS Satellite System

- 40,000 km transmission (>10 km)
- 200 Mbit/s
- 30 mW transmitter
- 0.8 μm wavelength
- Acquisition with 5 pW received power
- 8” aperture
- Present: 200W, 200 lbs
- Needed: Microoptical MEMs for tracking


MICROHELICOPTER
Transmitter
Solar Cell
Control Electronics
CCD
Rotor Blades

MIT-ARO MICROTURBINE



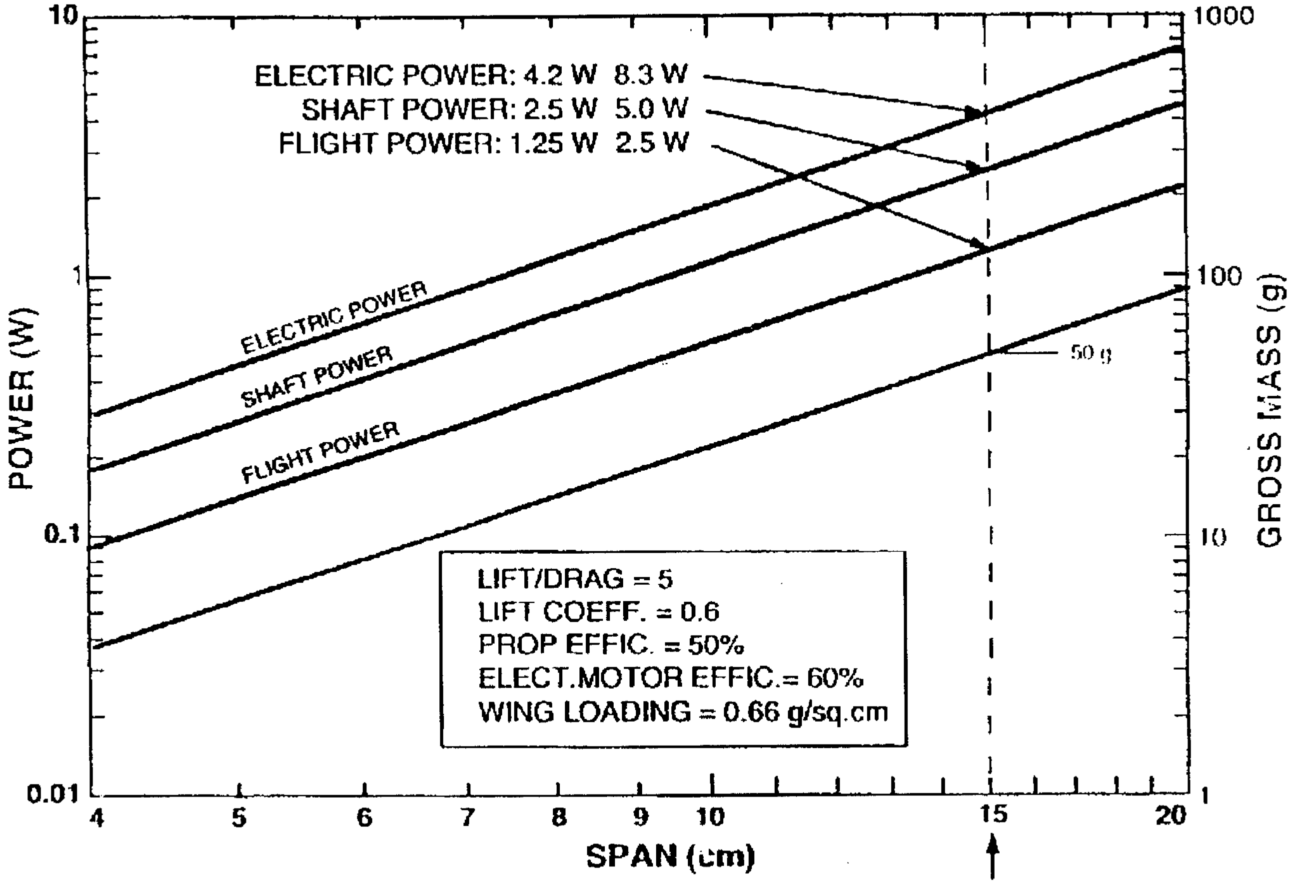
Conclusions

- Optical communications for MicroUAV are possible, but significant problems remain with acquisition and pointing stability
- Optical powering may solve weight and mission duration problems of MicroUAVs
- Optical ranging does allow removal of GPS antenna and processing hardware without loss of resolution
- Integration of parts essential to lower packaging size, weight and cost

MAV POWER REQUIREMENTS

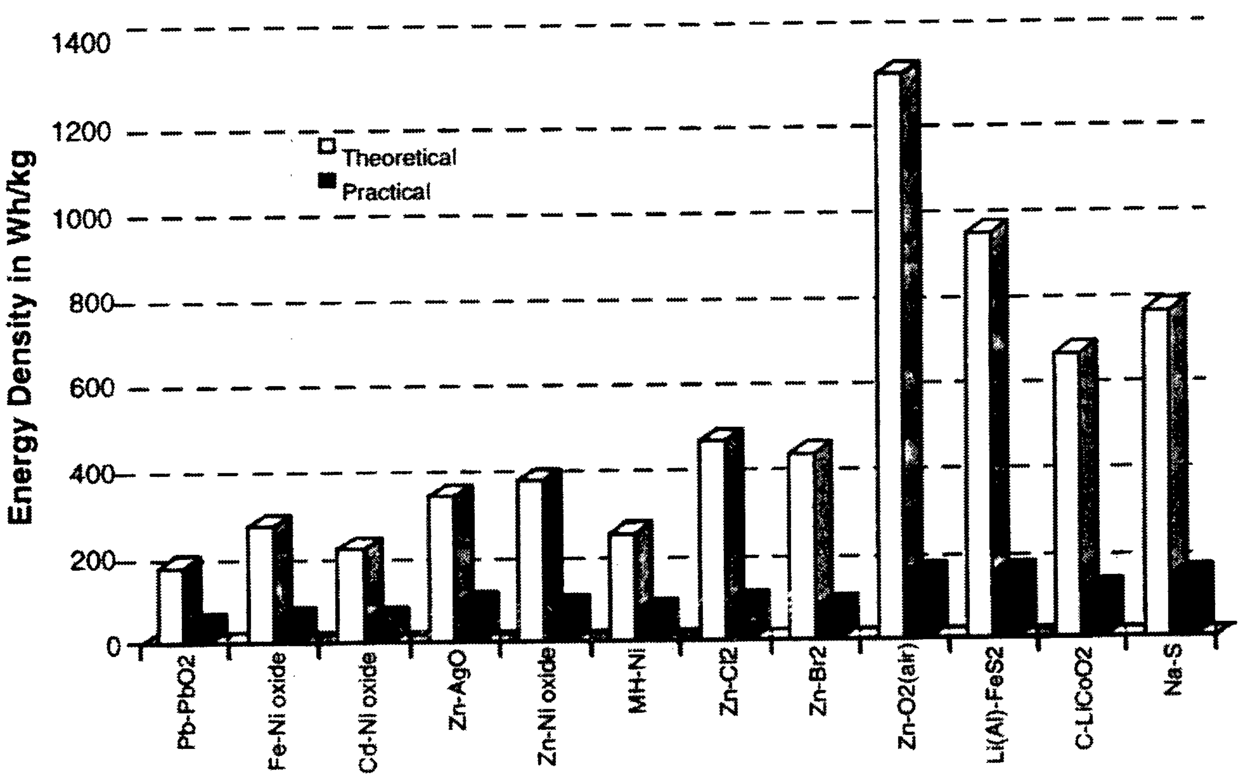
SEA LEVEL CRUISE AT 13 m/s

CLIMB / TURN: POWER MARGIN = 2



We can benchmark the upside potential of batteries by considering theoretical energy density, recognizing simultaneously that we will not capture all of the theoretical energy.

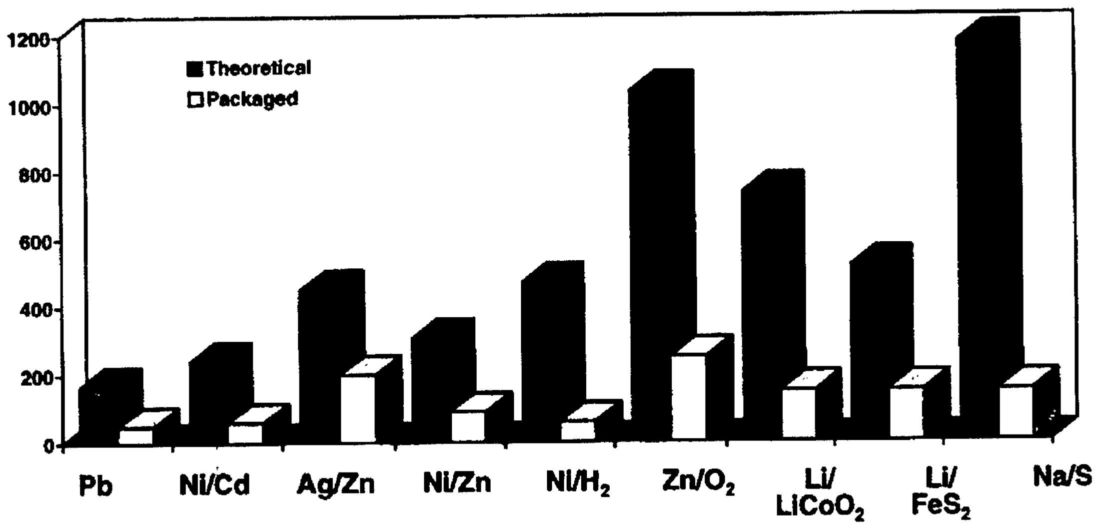
Secondary Batteries: Comparison of Theoretical and Practical Energy Densities



Arthur D Little

The ratio of packaged to theoretical energy density has proven to be less than 30% (which suggests one useful screening approach).

SPECIFIC ENERGY (Wh/kg)

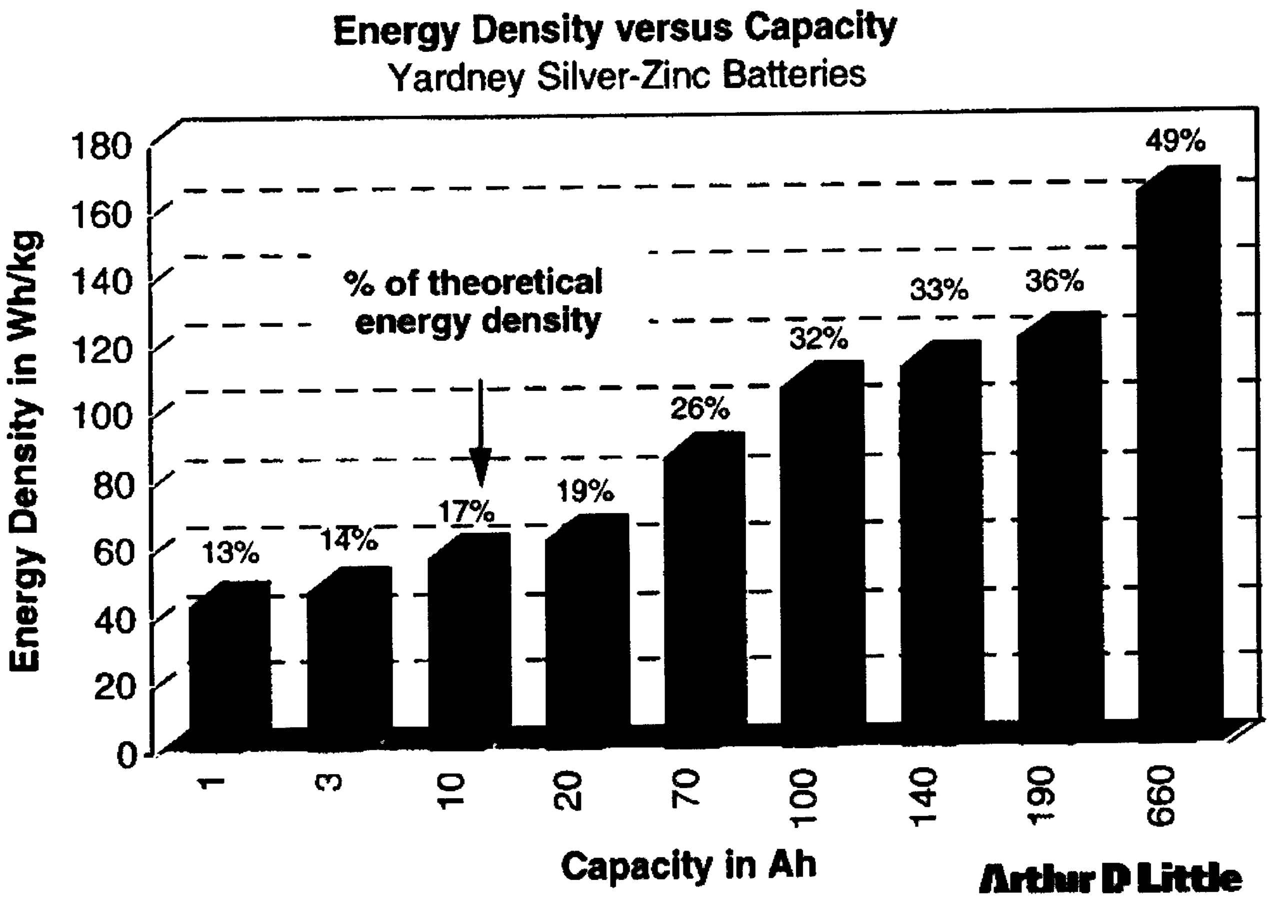


	Pb	Ni/Cd	Ag/Zn	Ni/Zn	Ni/H_2	Zn/O_2	Li/ LiCoO_2	Li/ FeS_2	Na/S
Theoretical	168	240	450	305	470	1,035	735	515	1,180
Packaged	50	60	200	90	60	250	150	150	150

SYSTEM

Arthur D Little

The ratio of practical energy density to theoretical energy density rises with increasing cell size.



Arthur D Little

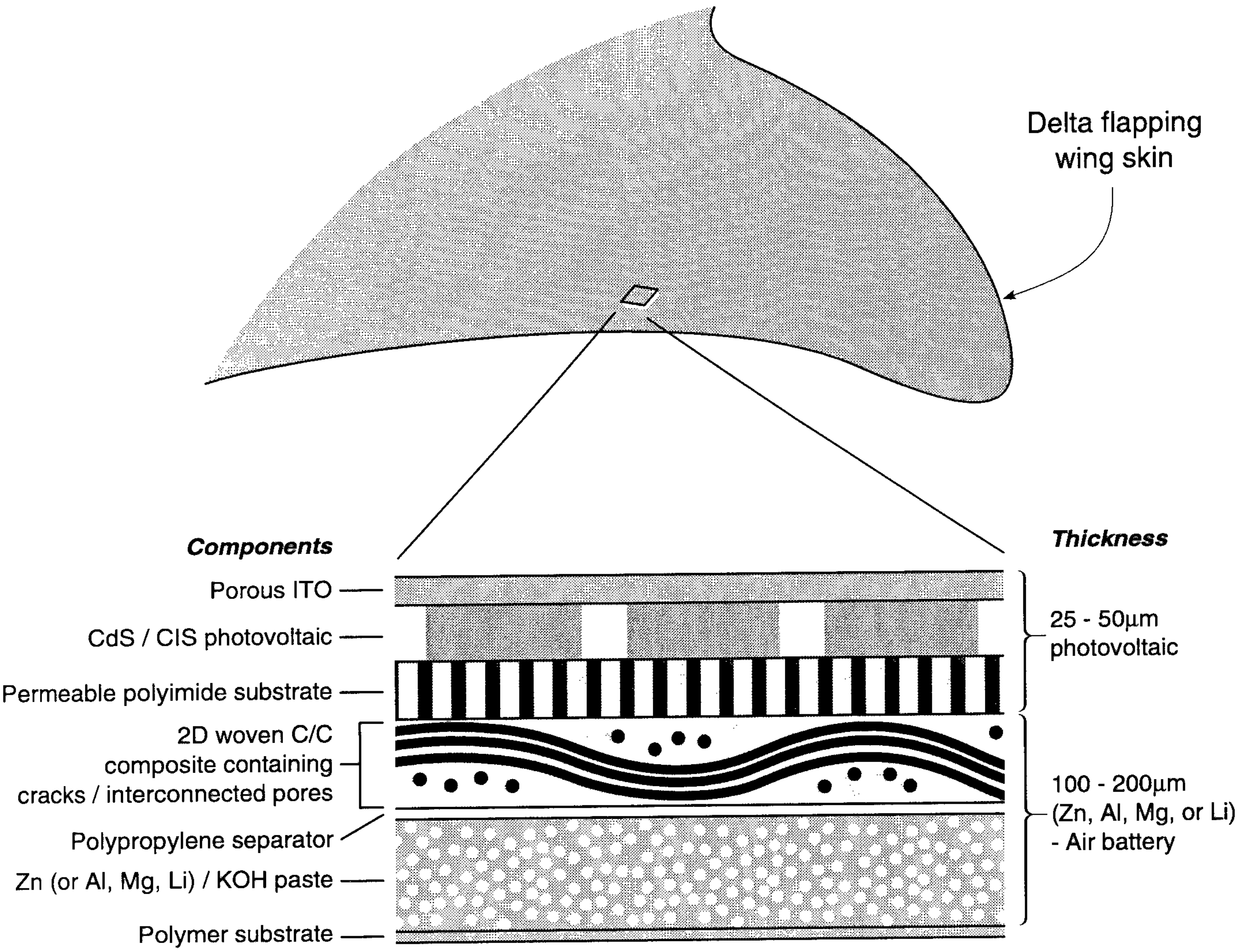
Flexible $CdS/CuInSe_2$ Photovoltaics

- ITN Energy Systems, Inc.
  - begins production 12/97
- 9% Module Efficiency (single crystal Si 12%)
  - 18% obtained on small area samples (single crystal Si 24%, GaAs 25%)
- > 500 W/Kg (versus approx. 50–100 W/kg for Si onkapton)
  - because of very high absorbtion only 1μm thick cell required (20 mils for crystalline silicon)

2392 flexible photovoltaics h wadley ipm 7/97

MULTIFUNCTIONAL WINGSKIN

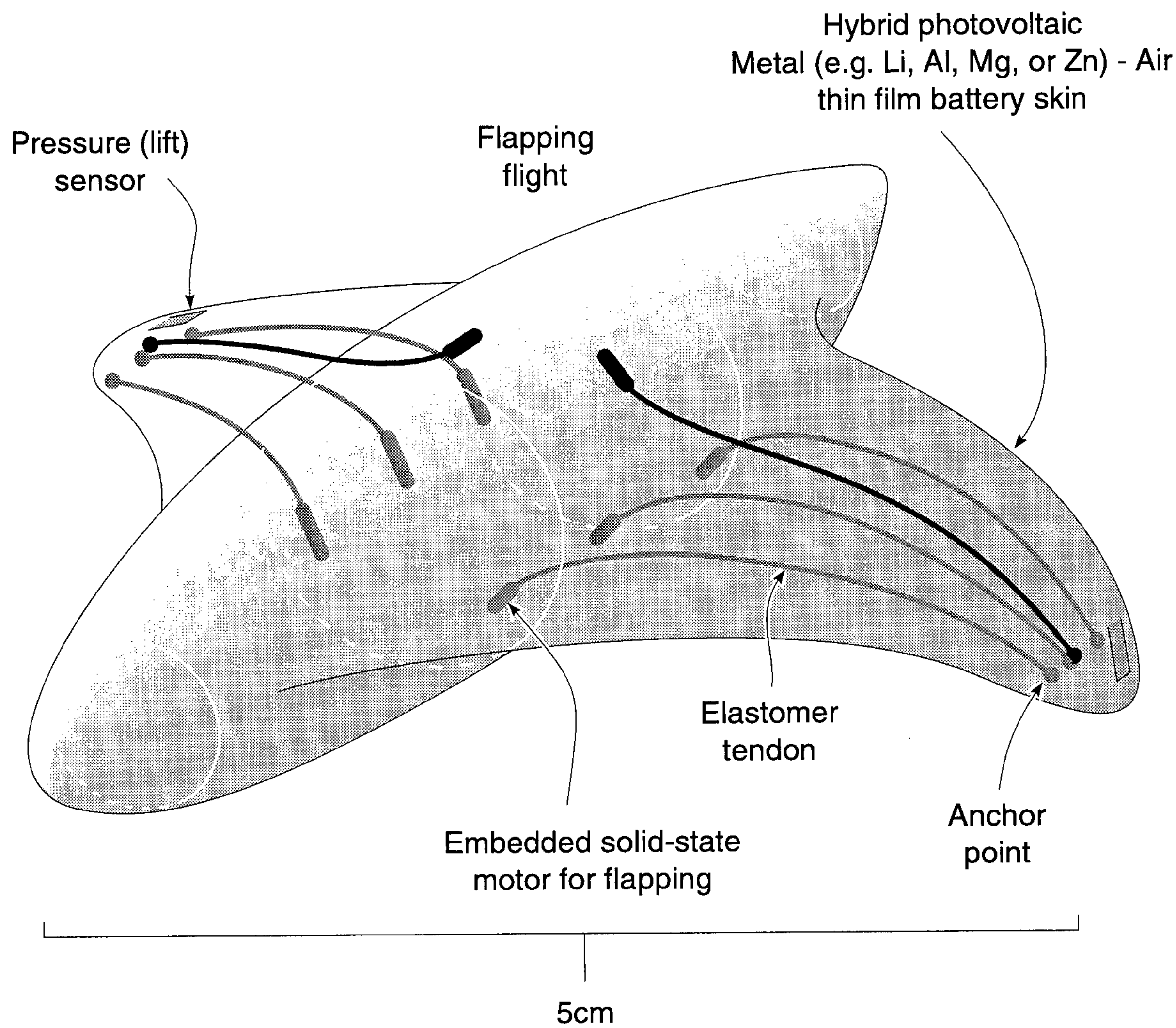
Light, stiff, thin film rechargeable battery, photovoltaic skin of a vehicle (e.g. next generation flapping system)



CONCEPT EXTENSIONS: Fuselage that extracts oxygen from air for an air-breathing fuel cell, regenerative fuel cell (e.g. H_2 from electrolysis / MEMS pump / buoyancy mechanism of lift).

2392 wingskin h wadley ipm 7/97

NEXT GENERATION AIR VEHICLE



2392 ray vehicle h wadley ipm 7/97

MULTIFUNCTIONAL DYNAMIC MATERIAL SYSTEMS

Workshop Organizers: A. Heuer, E. Hu, R. A. Reynolds

Monday, July 21, 1997

8:30 a.m.	**Objectives of Study: A Multispectral Imaging Chip** Arthur Heuer (CWRU), Bob Leheny (DARPA)
8:45 a.m.	**On-Chip Power** Brian Barnett (AD Little)
9:45 p.m.	**On-Chip Imaging Capabilities** Dan Kostishack (Lincoln Labs)
10:45 a.m.	Break
11:00 a.m.	**On-Chip Signal Processing** Ron Marquardt (RACAL Data Group)
12:00 p.m.	Lunch
1:00 p.m.	**On-Chip Communications: Millimeter/Microwave Communications** Larry Larson (University of California, San Diego)
2:00 p.m.	**On-Chip Communications: Optical Communications** John Bowers (UCSB)
3:00 p.m.	**On-Chip Signal Handling: Mixed Mode Technologies** Jim Cable (Peregrine Semiconductors)
4:00 p.m.	Discussion

Tuesday, July 22, 1997

8:00 a.m.	**Multifunctional Materials: Integration Issues** Rick Osgood (Columbia)
9:00 a.m.	**Discussion**
12:00 p.m.	**Lunch**
	Adjourn

MULTIFUNCTIONAL DYNAMIC MATERIAL SYSTEMS

July 21, 1997

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MULTIFUNCTIONAL DYNAMIC MATERIAL SYSTEMS

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NOVEL APPLICATIONS OF VLSI METHODOLOGY

D. Miller and G. Fuller

EXECUTIVE SUMMARY

Objective

To assess possible novel technological and applications areas where the concepts so successful in VLSI might enable new capabilities of potential interest to DoD.

DOD Relevance

DOD needs a broad variety of systems with low power, small size and weight, high functionality, and low cost. VLSI integration has helped achieve all of these for digital electronics. This study explores possibilities for applications for VLSI technology beyond digital electronics, and whether there are other technologies that could exploit a VLSI-like approach to achieve similar kinds of improvements.

Summary of Scientific & Technical Issues

VLSI Methodology

Very large scale integration (VLSI) of silicon transistors into integrated circuits is, at one level, a manufacturing technology, involving various highly-parallel processes, such as lithographic patterning. At another level, VLSI is also a *methodology*, a way of approaching problems that may transcend the physical technology. At its simplest, the methodology of VLSI is to take a large number of relatively simple components (transistors and wires), and combine them to perform complex functions of great value and utility (e.g., microprocessors). By concentrating on one scalable fabrication platform, almost regardless of the final application area, the cost can be reduced and the performance increased so much that the individual devices can be used extremely "inefficiently", and yet still save power, size, weight, and money; a modern inexpensive pocket radio will likely have many more active devices than its vacuum tube or discrete transistor predecessors, and yet perform better by any metric. The same technology can be used to make a radio, a computer, or a washing machine controller. The single, general-purpose, technology supplants separate, specialized ones.

VLSI methodology has several attributes that make it so successful, and any attempt to exploit the methodology beyond digital silicon should expect to show at least some of these.

- it uses simple building blocks
- useful functions can be made by combining these blocks (possibly in large numbers)
- the possible functions cover a broad range of applications
- the performance of the "blocks" (e.g., size, power, speed, cost) can be scaled (this allows designs and design tools to be reused as the technology improves)
- widely adopted standards and common interfaces develop

- flexible design tools emerge that reduce engineering cost and allow optimization for specific tasks

VLSI has also had performance improvements that followed well-defined scaling curves in time (e.g., Moore's law of the exponentially increasing number of transistors on a chip) that have reduced the risk of investment.

This is not to say that VLSI silicon is somehow a "perfect" technology. It has many weaknesses for specific applications. For example, silicon itself is not a very good sensor (with the notable exception of visible light sensors). Some aspects of silicon do not scale well (for example, wire interconnects), which interferes with the overall scaling of the technology and its applications. Silicon is rigid, flat, and brittle. Digital silicon circuits, though impressive in their performance, do not have low enough power consumption for some demanding tasks. Some applications call for distributed functions, of moderate capability, over large areas (e.g., displays, body sensors), which cannot be handled by silicon on its own. The question for this study is not whether these problems can be solved for digital silicon, but whether there are other ways of using silicon technology, or other technologies altogether, while still taking advantage of the kinds of attributes that have made digital silicon VLSI so successful in its application domains.

It is worth noting that the leap to a VLSI methodology in a given area may be counter-intuitive at first; it may involve moving away from the evolutionary improvement of a given high performance device towards extracting ultimately higher system performance from a large number of less capable devices. Consequently, carefully targeted research programs may be necessary at first to stimulate counter-intuitive thinking and solutions, but their ultimate leverage could be high. As an additional motivation, it is useful to remember that biological systems often adopt the approach of a large number of simple (and sometimes even unreliable) components to outperform many man-made systems (e.g., in sensing and understanding the environment).

Coverage of This Study

One of the early conclusions of this study was that there are many areas where such a VLSI methodology might be applicable. The study deliberately took a broad view of the possibilities, rather than focusing tightly on particular ones. Such focusing remains a possibility for the future. The study did not examine VLSI technology itself; this has been well covered in other workshops and studies. The area of silicon micro-electro-mechanical systems (MEMs) was also largely avoided because it has been dealt with elsewhere. The areas investigated included

- analog VLSI, biomimetic sensor arrays, and associated processing architectures
- patterned biological neurons
- optics
- chemical "laboratory on a chip"
- chemical sensor arrays
- alternate patterning schemes (printing and weaving as opposed to lithography)

The first four areas above are largely attempts to exploit existing VLSI techniques in other areas; the last two are areas that might exploit the methodology but with different technological approaches.

Analog VLSI, Biomimetic Sensor Arrays, and Associated Processing Architectures

Digital technology can achieve arbitrary accuracy, but it does so by making very poor use of the accuracy available in any individual device. Conventional analog processing, investigated for many years in analog computers that attempted, for example, to solve differential equations, runs into substantial problems of limited accuracy and accumulation of error. The continuing exponential development of VLSI digital technology meant that it supplanted essentially all such analog processing. VLSI technology can, however, also be used to make analog circuits. It appears that, with new kinds of architectures that operate with a mixture of analog and digital or "quasi-digital" (nonlinear analog) circuits, improved performance could be obtained with such systems; such architectures would allow low precision analog circuits to form a useful part of systems that overall have high accuracy. The key difference compared to previous analog systems is the current trend to low precision distributed systems compared to a high precision "single path" analog system. A particular advantage of the analog circuits is that they can have substantially lower power consumption (and circuit area) than digital circuits performing the same function; a simple resistive adder, for example, requires much less circuitry than the digital circuits that would perform the same function. In many DoD systems, power and size are very critical, and there are many potential applications where we cannot get enough processing out of digital circuits at tolerable power and weight; examples would include sensor processing on small autonomous vehicles where the lack of sensor preprocessing puts large demands on the communications channel bandwidth (and therefore power, weight and size).

An important difference for analog circuits made in VLSI technology and mixed with digital circuits, is that, compared to previous analog computing, they would not be overtaken by the advances in the digital technology. As the VLSI digital performance improves with advancing generations, so also does the analog performance.

A second reason for being interested in analog VLSI is that it is a technology well suited to doing sensor processing in sensor systems that are closer in concept to the way biological sensors work. Specifically, many biological sensors (e.g., cochleas (ears), chemical "noses", "fly's eye" collision avoidance) operate by running large numbers of relatively low precision sensors, at low to moderate speeds, but massively in parallel, extracting the key elements of information with large amounts of dedicated "quasi-digital" analog processing. Biological sensors can have very impressive performance, partly because they use adaptive processing as part of the sensing process; the cochlea, for example, has a dynamic range of 120 dB, and a power consumption of 14 microwatts. The broad dynamic range is achieved with a low-precision sensor because the sensors locally adapt to the overall level, a concept that requires local processing as part of the sensing function; this is a principle found extensively in biological sensor systems. Artificial "vision" chips with integrated adaptive processing can operate to extract edges or detect motion despite wide variations of light level within a given image because the sensors adapt to the local light level. A "dumb" camera with only a single gain control cannot do this, and will run into dynamic range difficulties.

There has been work at a scientific level on understanding biological architectures, for example in the ear and in vision, for some time. Research has demonstrated various

"vision" chips, including, for example, sensor and processing arrays designed to estimate motion or "time to impact". Such systems require only moderately large number of sensors in an array (e.g., 30 x 30, as in a fruit fly) to provide useful outputs. There is a relatively good understanding at the basic level of the trade-off between analog and digital circuits in processing. There is also some work now on making high precision machines incorporating low-precision, low-power, analog circuitry. It does not appear, however, that these approaches have been seriously investigated for the potential for satisfying future military requirements. This seems like an area ripe for investigation and possible exploitation. It has the advantage that it is not apparently necessary to develop substantial new hardware technologies to investigate it, since it would merely exploit existing VLSI technology. The more important physical aspects would be integration of sensors arrays of various kinds, most likely by high-performance bump-bonding or other high density integration techniques, and possibly exploration of highly parallel interconnect technology, such as array optical interconnects, that would map well onto the highly parallel architectures favored by these kinds of systems.

Patterned Biological Cells

There has been substantial progress in controlling the growth of biological cells using patterning of silicon substrates. We are still a long way from engineering biological neurons together with other information processing technologies. There is, however, substantial scientific progress in this area that may also yield more understanding about how neural information processing actually works. VLSI technologies are likely to be very useful here, for example, to create patterns to impose on neuron growth, and to form electrical sensing and stimulus "contacts" to the biological structures. There is considerable scope for using more sophisticated VLSI fabrication techniques in the future of this scientific work.

Though patterned growth of brains is a long way off (and is not the goal of current research), it might be that techniques like these could be used for integrating chemical and biological warfare sensors together with silicon electronics for processing the resulting sensor signals. This is certainly a speculative suggestion, but one that might be worth exploring further. Certainly it is desirable to know how to interface biological systems with conventional silicon processing technology. From the point of view of sensors, it is known that cells are capable of an immense amount of "amplification" of an initial stimulus, though there are certainly basic challenges in making cells long-lived for use on sensors.

Another possible use is as an alternative to the use of laboratory mice; cells of a particular organ might be cultured for testing with various reagents (a so-called "mouse on a chip"), with the results being read out either through the silicon chip or by some other technique (e.g., optical). Such techniques would be of considerable use for research purposes, and for applications such as drug screening or toxicology. The actual motivation behind the current research is towards controlling neural regrowth, for example for repair of damaged nerve cells in the body, which is of considerable interest to DoD for therapeutic use on the injured.

Optics

There is already one well-developed technology in optics that uses VLSI techniques, namely diffractive optics. In diffractive optics, a pattern, typically varying on the scale of an optical wavelength, is etched or stamped into a planar material. Through diffractive effects, the resulting optical element can perform various different kinds of functions, such as lenses, aberration correctors for other lenses, diffraction gratings for wavelength selective behavior,

or custom optical interconnection patterns. This technique is likely to see increasing use, and is particularly good at building complex optical elements.

Another area of research that appears to have progressed substantially is the connecting of arrays of optoelectronic devices to silicon VLSI circuits by hybrid techniques. Thousands of optical devices have now been hybridized to a single chip. Such techniques may enable new classes of optoelectronic systems for interconnects or for sensing applications, avoiding some of the limitations of wired interconnects, and permitting optoelectronic systems approaching VLSI complexity.

An area of current research is the forming of complex waveguide structures in a substrate to make optical "circuits". Such circuits can have uses at the physical layer of optical networks, performing functions such as wavelength division de-multiplexing, filtering, signal distribution. The small size and weight of such integrated components could be useful for DoD applications such as networking on platforms. Some of the approaches are compatible with the fabrication of silicon VLSI circuits, in principle allowing integration with active silicon processors. A problem here is that the optoelectronic devices for providing optical outputs (through modulation or light emission) are still somewhat speculative if they must be monolithically integrated with silicon. The integration of waveguides is also currently limited in its density by the requirements of relatively large radii of curvature in the waveguides if losses are not to be too high.

Another area of current research is in using silicon micromechanical techniques to make optical assemblies on the scale of 100s of microns. These techniques allow the construction of optical systems of lenses, mirrors and optoelectronic devices, where the alignment of the elements can be adjusted through the use of micromechanical motors. This is a promising technique that merits further research to find out where and how it can best be exploited. It represents a new option in the difficult task of packaging optoelectronic systems.

Chemical "Laboratory on a Chip"

Lithographic technology allows the construction of microscopic chemical "reactors". Patterned channels on a glass plate allow very small quantities of chemicals to be pumped by electrically controlled techniques such as electrophoresis, and controllably mixed. The resulting mixture can be probed by optical flourescence techniques to study the result. This provides an interesting new chemical analysis technique, with a broad range of potential applications.

At the present time, such systems are still relatively simple (though still useful). Large scale integration might be possible, though the utility of such larger systems is not so clear unless some controllable or "active" devices such as valves can also be integrated to allow more complex functions. Another possible extension would be to a "two-level" patterning that would allow arbitrary patterns of interconnected channels. There is clearly opportunity here for more research.

Chemical Sensor Arrays

As has been mentioned above, arrays of multiple simple sensors have significant potential, emulating as they do the approaches of biological sensor systems. Often, chemical or biological sensors are most conveniently read out optically, through luminescence. One novel approach to making such optically read sensor arrays uses arrays of optical fibers. Such fiber arrays already exist for conveying images from one end to the other. Such fiber

arrays can be formed into a single fiber-like unit, known as an imaging fiber, with multiple individual cores of micron dimensions. Different sensing chemicals can be deposited on different parts of the surface of this imaging fiber. As a result a set of sensors can be constructed that can be read out by optically exciting the chemicals and monitoring the resulting luminescence and its variation in time. This technique, with appropriate processing of the resulting image of luminescence signals, can be quite a sensitive discriminator of chemicals, giving an artificial "nose". In such a sensor array, the detection of a given stimulus ("smell") reduces to a pattern recognition task, with the pattern being in space and time in this case.

This type of sensor would be very well suited to integration with an optical sensor array and suitable processing or preprocessing electronics, which could lead to very small, smart chemical sensors. It appears there is considerable potential in such approaches to chemical (and possibly biological) sensing.

Alternate Patterning Schemes

There are prospects for using printing technologies (as in laser or ink-jet printers) for fabricating complex circuits, though usually at a length scale above those used in silicon VLSI. At the present time, variants of commercial printing technologies are largely used for such experiments, with available resolutions down to about 20 microns. It may be that there are opportunities for much finer printing, though this would likely require some research; printing down to the 2 micron scale would allow a much broader range of applications, including printed microelectronics. Printing has the advantage that, in contrast with lithography, it can be used on flexible materials, can be very inexpensive for large areas, and it can be an entirely "additive" process (with no subtractive etching). Printing can also be performed on non-planar substrates; it is quite possible to print a helical wiring pattern round a fiber or other cylinder, for example, for "micro-transformers". Printing may be usable with materials not suited to the kinds of evaporative or chemical growth processes used in VLSI fabrication; such options might become useful for chemical and biological sensing materials, for example.

Weaving active fibers (e.g., metal wires, optical fibers) is also quite possible as an alternate technology for flexible materials, possibly in combination with printing the resulting fabric with other circuits or even devices. Such techniques are being researched now for possible applications as wearable circuit garments allowing sensing of wounds. Another possible fabrication technology is "stamping" at small size scales. Stamping differs from the kind of printing discussed above in that it requires the construction of a stamp, possibly by lithographic or other processes, but resolutions in stamping processes can be very fine, possibly down to 100 nm.

Conclusions and Observations

Observations

- a major potential use of aspects of VLSI methodology is in integrating sensors and sensor processing

    DoD has a broad range of sensor needs

    integration could reduce power, size, weight, and cost

identification of a small number of "universal" sensor platforms could be very effective in improving performance/cost

- making sensors systems from multiple, simple sensors with integrated local processing, e.g.,

    to adapt their level to give larger dynamic range

    to extract key local features

  is a promising approach that is inspired by biological sensing, and that could become a flexible platform for many different kinds of sensing

    e.g., chemical, biological, audio, motion, image preprocessing

- techniques to integrate diverse kinds of sensor arrays with silicon are very important

    other than for visible light detection, silicon itself will usually not be the sensor

    sensor materials and fabrication will usually not be compatible with silicon fabrication or processing

  hybrid integration techniques will therefore be important, e.g.,

    low parasitic capacitance solder bonding for sensor arrays with electrical readout

    chemical/biological sensor read out using optical arrays

    chemical/biological electrical interface to silicon

- there is a need for better understanding of the interfacial chemistry between biological materials and silicon technology, to allow more extensive use of biological sensors read out by silicon

- analog VLSI is ready for serious investigation for sensor preprocessing for

    reduction of power, size, and weight

    sensors that exploit principles of biological sensing systems, including

      large dynamic range

      effective utilization of large numbers of simple sensors for complex tasks

- techniques such as printing, stamping, and weaving could be used for fabrication of complex circuits and even active devices, opening up possibilities for

    large, flexible, non-planar, or conformal substrates,

    use of materials (such as chemical and biological materials) not suited to the processes used in VLSI

    materials for corrosive environments

- optics could benefit from more application of VLSI methodology

    reduce size and weight by integration

    move towards array packaging not based on single device packaging

- array optics may be useful for readout of sensor arrays and for interconnecting highly parallel sensor processing systems

Conclusions

A few major conclusions from this study are as follows

- it may be time to explore a novel sensing paradigm for DoD applications

  many simple sensors, with adaptive local processing

- integration of many different kinds of sensors with silicon processors will be important

  needs more integration technologies

- exploit analog VLSI

  well suited for reducing power, size and weight, and for working with sensor arrays with local processing

- there are alternate patterning technologies that could be used with materials not suited to silicon-like processing techniques

Novel Applications of VLSI Methodology

DSRC
DEFENSE SCIENCES RESEARCH COUNCIL

David Miller and Gene Fuller

Objective

- **To assess possible novel technological and applications areas where the concepts so successful in VLSI might enable new capabilities of potential interest to DoD.**

Relevance to DoD

- **DOD needs a broad variety of systems with**
  - *low power, small size and weight, high functionality*
- **low cost. VLSI integration has helped achieve all of these for digital electronics**
- **this study explores**
  - *possibilities for applications for VLSI technology beyond digital electronics,*
  - *whether there are other technologies that could exploit a VLSI-like approach to achieve similar kinds of improvements.*

Scientific and Technical Summary

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Attributes of VLSI "methodology"

- simple building blocks
- useful functions by combining those blocks in large numbers
- performance of blocks scales
- widely adopted standards and interfaces
- flexible design tools
- predictable performance improvements

Note - silicon has its weaknesses

- not a good sensor (except for visible light)
- wiring does not scale well
- rigid, flat, brittle, limited size

Applying VLSI methodology in other areas counter-intuitive

- move away from evolutionary performance improvement of a given device
  - *better system performance from large number of less capable devices*
  - *existence proof - biological systems*

Scientific and Technical Summary

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areas covered in this workshop include

- **exploiting VLSI technology in new ways**
  - *analog VLSi, biomimetic sensor arrays, and associated processing architectures*
  - *patterned biological cells*
  - *optics*
  - *chemical laboratory on a chip*
- **exploiting VLSI methodology with other technologies**
  - *chemical sensor arrays*
  - *alternate patterning schemes*

Analog VLSI

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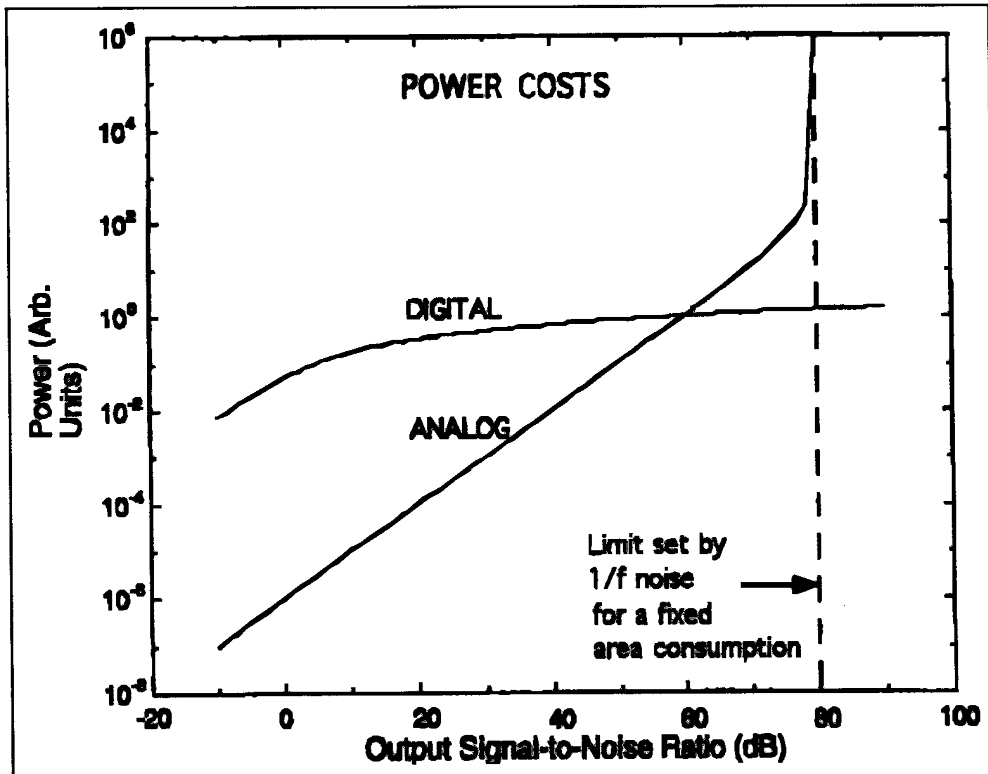
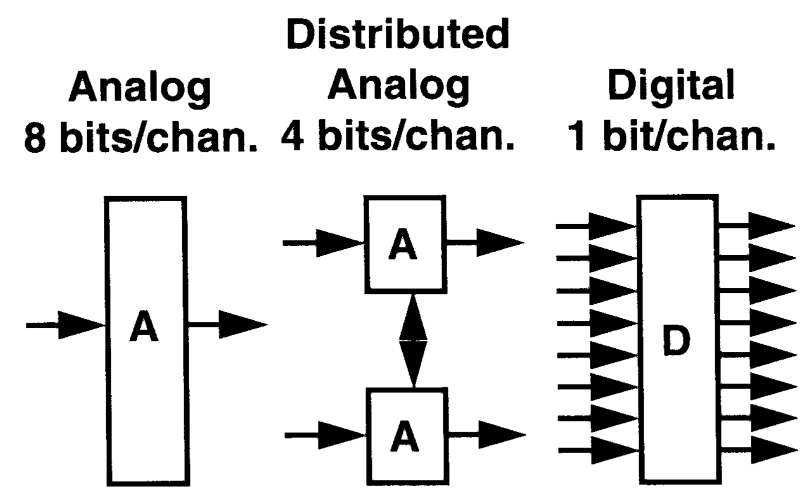


- analog lower precision, lower power
- distributed analog allows advantages of analog and digital
- very attractive for preprocessing in sensor arrays

VLSI Cochlea Power

Analog	ASIC	Micro-Processor
0.5 mW	150 mW	50 W
7.7 mm^2 (1.2 µm tech.)	25 mm^2 (0.5 µm tech.)	299 mm^2 (0.5 µm tech.)



Biomimetic sensor arrays

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arrays of low precision, simple sensors, with integrated processing allow

- **sophisticated sensing functions (audio, chemical, biological, motion, image preprocessing)**
- **with high dynamic range because of adaptive sensing using built-in processing**
  - *biological cochlea (ear) has 120 dB dynamic range and 14 microwatts of power consumption*

Fly's eye motion detection and collision avoidance

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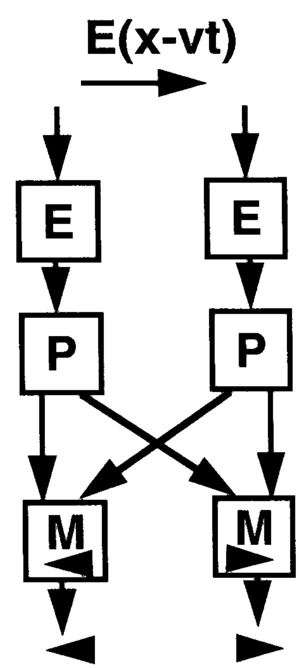


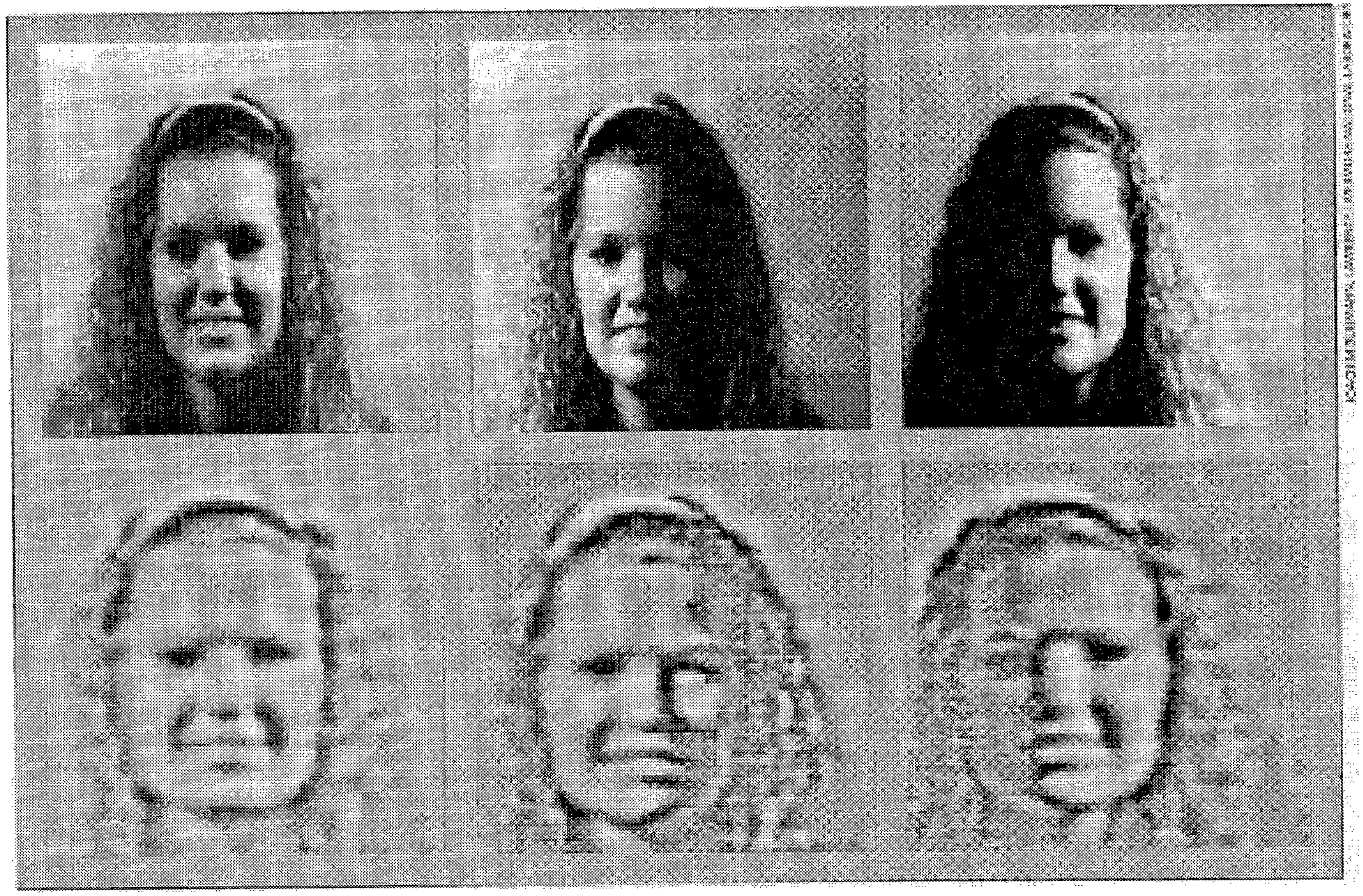
local processing between neighbors detects motion and direction

30 x 30 array of simple sensors with built-in processing detects motion and "point of impact"

Vision chip

CCD camera

analog VLSI imager with local adaptive processing



analog VLSI processing built in with the sensors adapts to the local intensity in the image to extract low precision (but useful) information with high overall dynamic range

Patterned Growth of Neurons

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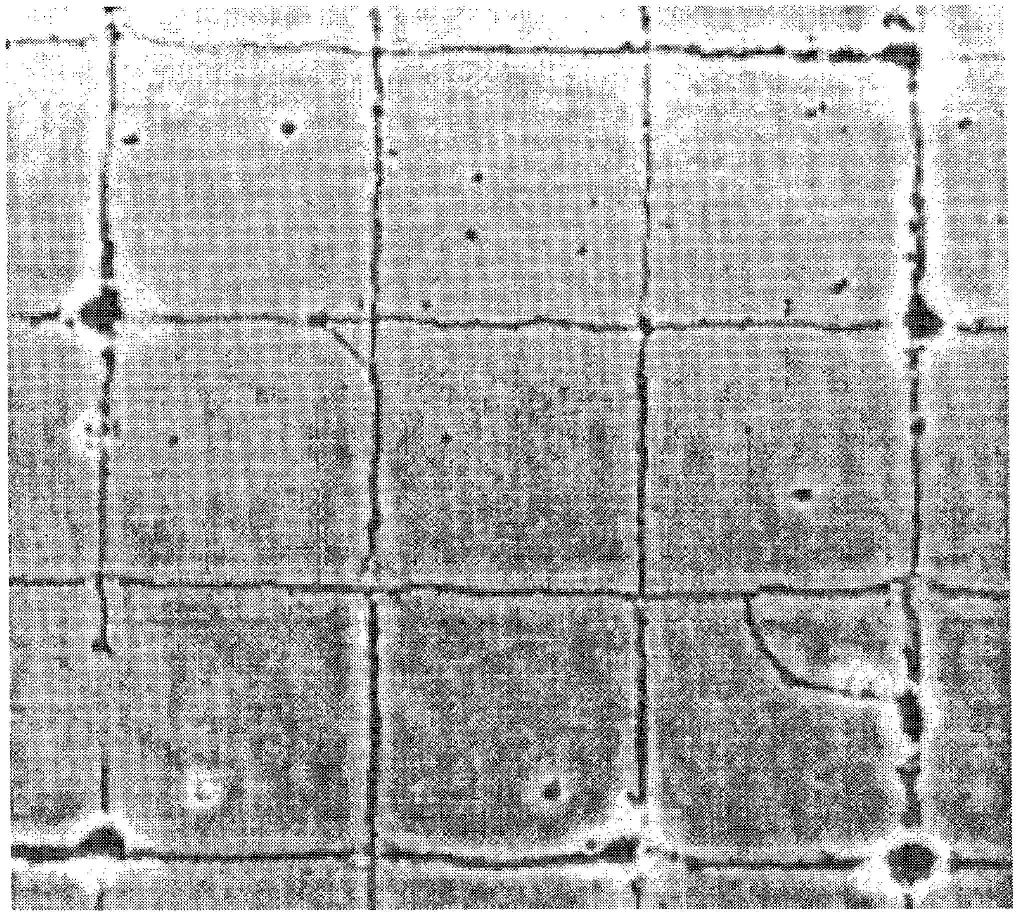
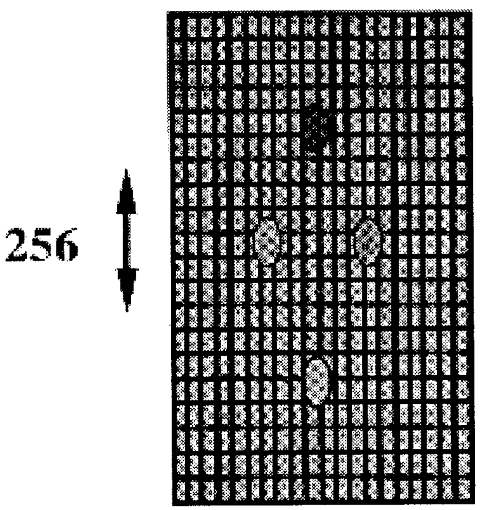
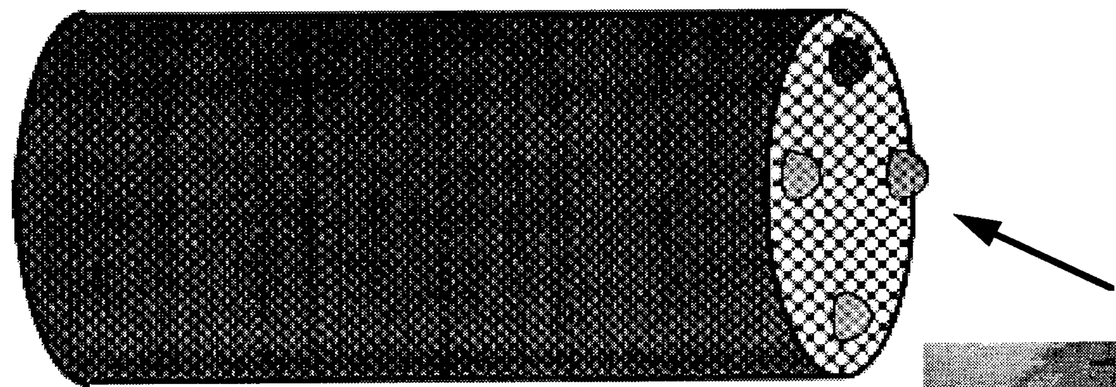
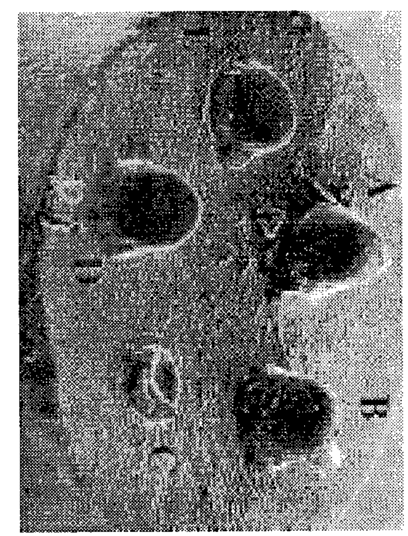


- patterning of silicon substrate can be used to encourage neurons to grow in particular patterns
- useful for studying biological neural networks, and possibly ultimately for controlled growth of, e.g., biological sensors (Wheeler et al. (U. Illinois))

Chemical sensing with fiber array







luminescence from different sensing ("indicating") chemicals is detected on the CCD and the stimulating chemical ("smell") is deduced from the composite response (Walt et al. (Tufts Univ.))

"Next generation" fiber sensor array

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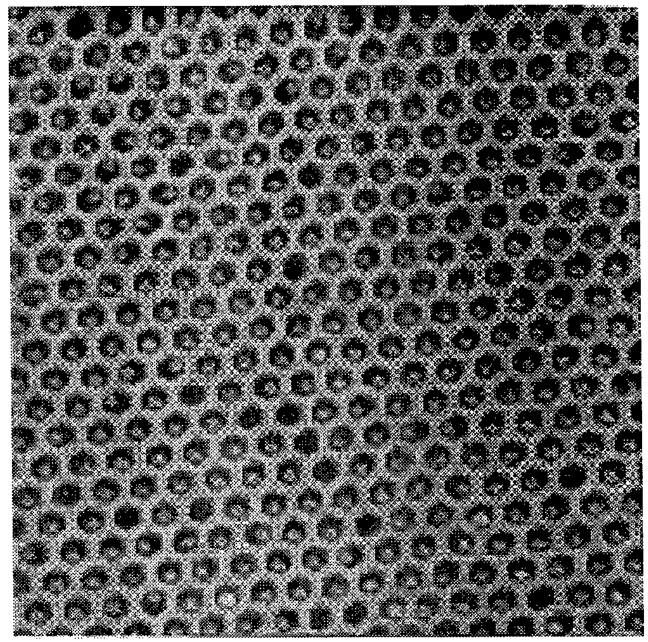

3.1 micron diameter microspheres, coated with various sensing chemicals, in 36 fL microwells on end of imaging fiber

Walt et al. (Tufts Univ.)

Silicon micromechanical technology for optical assemblies

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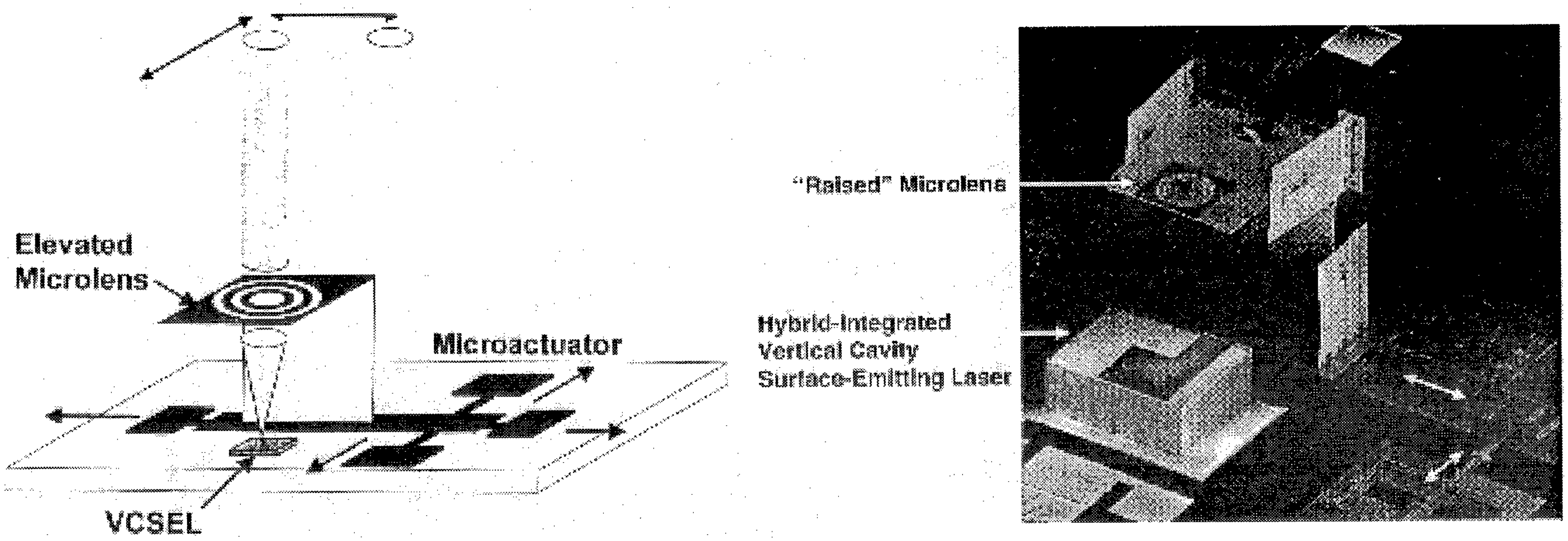
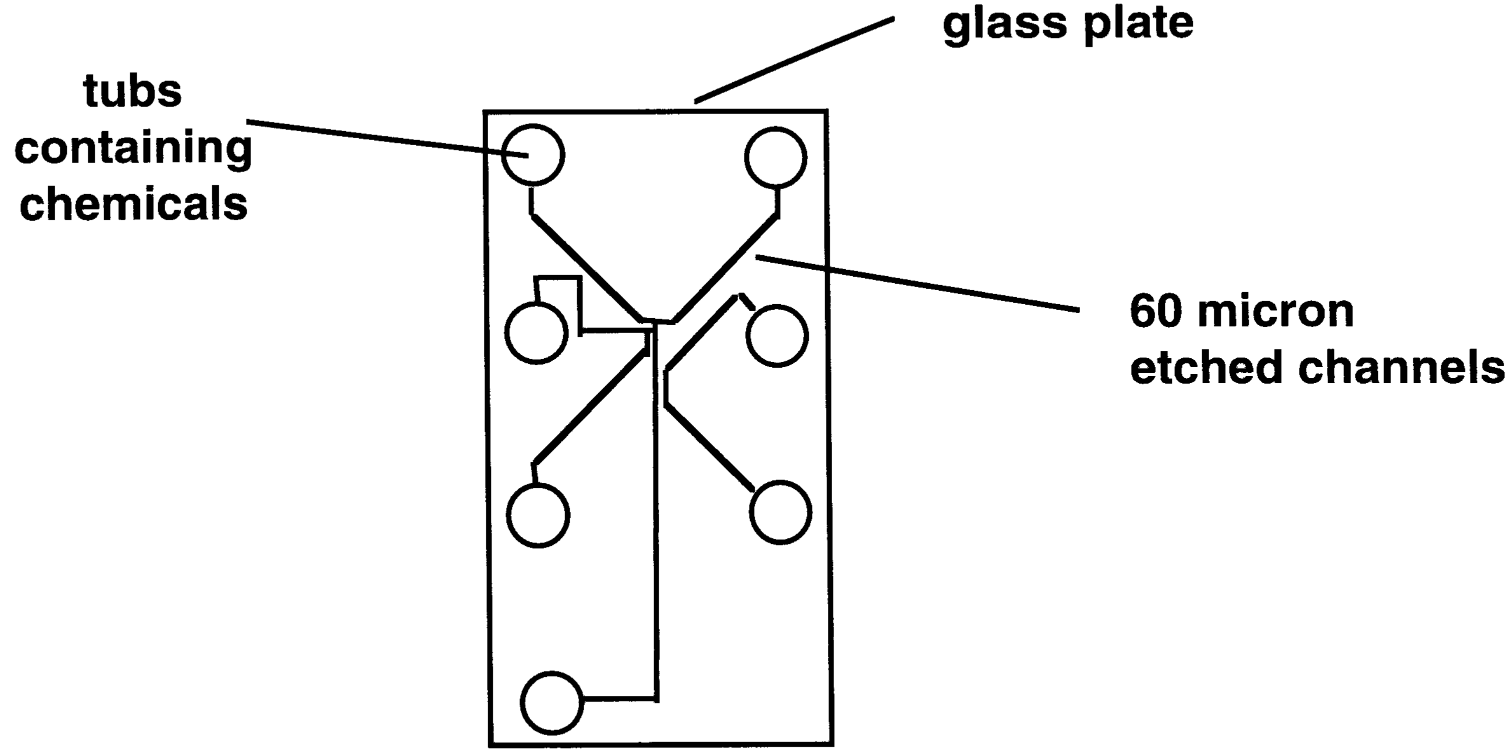


example solution to difficult packaging and integration problems in optics using VLSI technology (Wu at al. (UCLA))

Microchemical reactors



applying voltages to electrodes in tubs causes chemicals to pump through channels in glass plate

result of controlled mixing is observed through optical flourescence in channel at end of mixing process (Bousse et al. (Caliper Tech. Corp.))

Stamping for Pattern Transfer

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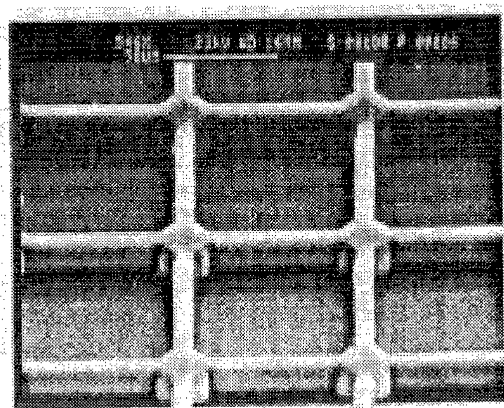
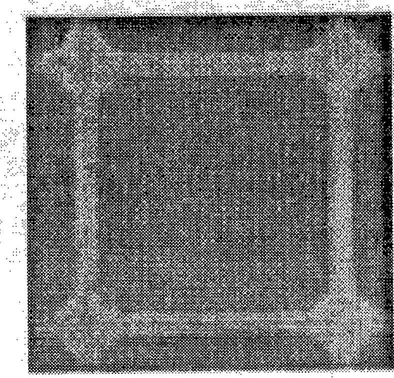


SEM of stamp:
Relief: 20 um
Line Width: 5 um
Node Diameter: 15 um
Node Separation: 80 um



Transferred Stamp Pattern
FITC (fluorescein isothiocyanate)
labeled poly-L-lysine on glass coverslips

possible alternate technique for patterning of different materials

Wheeler et al. (U. Illinois); Whitesides et al. (Harvard)

Wearable Circuit Garments

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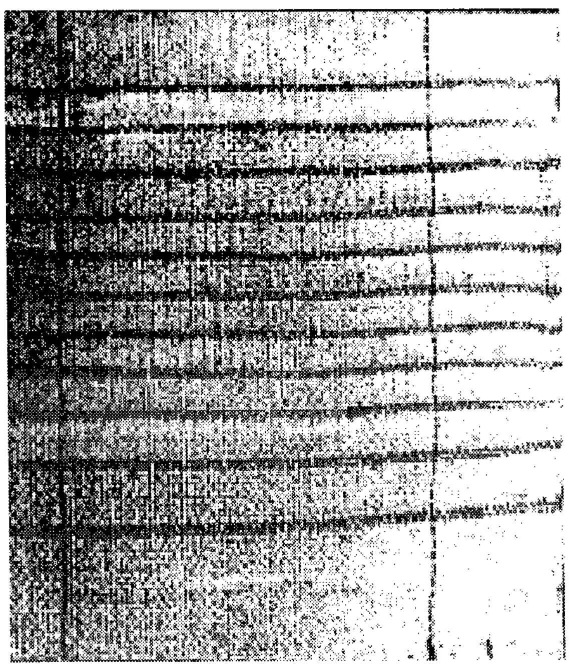

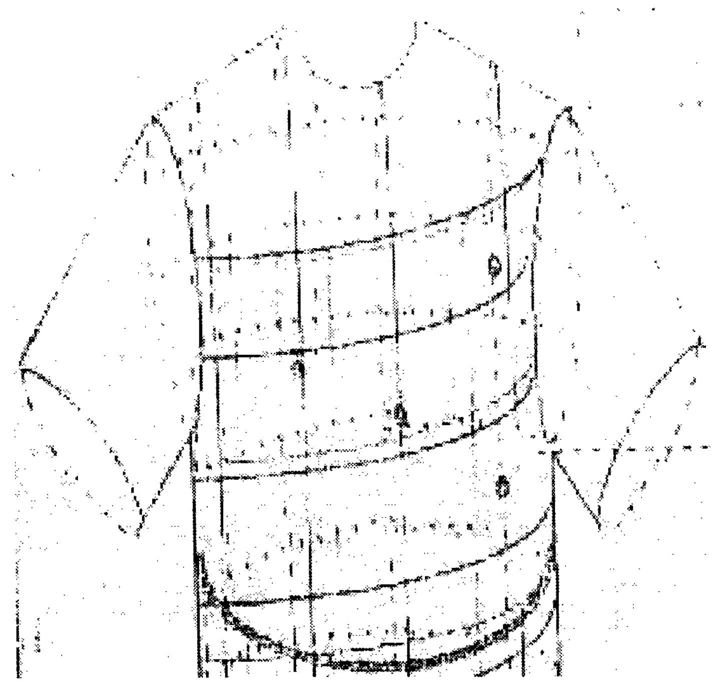

- can weave electrical and/or optical fibers into fabric for wearable circuit garments or sensate liner
- current goal - improve triage by detecting wounds (Lind et al. (NRaD)

Observations

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a major potential use for VLSI methodology is in integrating sensors and sensor processing

- integration could reduce power, size, weight, and cost
- want small number of "universal" sensor platforms

make sensors systems from multiple, simple sensors with integrated local processing, e.g.,

  - *to adapt their level to give larger dynamic range*
  - *to extract key local features*

- promising approach inspired by biological sensing
- might become a flexible platform for many different kinds of sensing
  - *e.g., chemical, biological, audio, motion, image preprocessing*

Observations

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techniques to integrate diverse kinds of sensor arrays with silicon are very important

- other than for visible light detection, silicon itself will usually not be the sensor
- sensor materials and fabrication will usually not be compatible with silicon fabrication or processing

hybrid integration techniques will therefore be important, e.g.,

- low parasitic capacitance solder bonding for sensor arrays with electrical readout
- chemical/biological sensor read out using optical arrays
- chemical/biological electrical interface to silicon

need for better understanding of the interfacial chemistry between biological materials and silicon technology

Observations

analog VLSI is ready for serious investigation for sensor preprocessing for

- reduction of power, size, and weight
- sensors that exploit principles of biological sensing systems, including
  - *large dynamic range*
  - *effective utilization of large numbers of simple sensors for complex tasks*

techniques such as printing, stamping, and weaving could be used for fabrication of complex circuits and even active devices, opening up possibilities for

- large, flexible, non-planar, or conformal substrates,
- use of materials (such as chemical and biological materials) not suited to the processes used in VLSI
- materials for corrosive environments

Observations

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optics could benefit from more application of VLSI methodology

- reduce size and weight by integration
- move towards array packaging not based on single device packaging

array optics may be useful for readout of sensor arrays and for interconnecting highly parallel sensor processing systems

Conclusions

may be time to explore novel sensing paradigm

- many simple sensors, with adaptive local processing

pursue integration of many different kinds of sensors with silicon processors

- needs more integration technologies

exploit analog VLSI

there are alternate patterning technologies that could be used with materials not suited to silicon-like processing techniques

APPLYING VLSI METHODOLOGY IN NEW CONTEXTS

Study Organizers: D. Miller and G. Fuller

Wednesday, July 23, 1997

8:15 a.m.	**Welcome**
8:30 a.m.	**VLSI: Analog Versus Digital** Rahul Sarpeshkar (Bell Labs/MIT)
9:15 a.m.	**Neuromorphic Architectures and Applications** Christoph Koch (Caltech)
10:00 a.m.	**Break**
10:30 a.m.	**Micropatterned Neuronal Networks** Bruce Wheeler (University of Illinois)
11:15 a.m.	**Discussion**
11:45 a.m.	**Lunch**
12:45 p.m.	**Optical Sensor Arrays, Microarrays, and Nanoarrays** David Walt (Tufts University)
1:30 p.m.	**Microfoundries for New Materials** George Whitesides
2:15 p.m.	**Break**
2:30 p.m.	**Silicon on Insulator Photonic Integrated Circuits (SOIPIC)** Bahram Jalali (UCLA)
3:15 p.m.	**Micro-Optics Realized by VLSI Technology** Ming Wu (UCLA)
4:00 p.m.	**Discussion**
4:30 p.m.	**End of Formal Activities for the Day**
6:00 p.m.	**Dinner**

APPLYING VLSI METHODOLOGY IN NEW CONTEXTS

Study Organizers: D. Miller and G. Fuller

Thursday, July 24, 1997

8:00 a.m.	**Laboratory on a Chip** Luc Bousse (Caliper Technologies)
8:45 a.m.	**Wearable Circuit Garmet Technology** Eric Lind (NCCOSC)
9:30 a.m.	**Break**
10:00 a.m.	**Structured Discussion**
Noon	**End of Workshop**

APPLYING VLSI METHODOLOGY IN NEW CONTEXTS

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JUST IN TIME ELECTRONICS FOR WEAPON SYSTEMS

T. C. McGill, B. K. Gilbert, and R. M. Osgood

EXECUTIVE SUMMARY

Objective

The purpose of this study was to determine whether or not the DoD need for electronics could be fulfilled totally by COTS. In particular the study aimed at determining what the services felt that they might require in non-COTS electronics. We then carried out an in-depth study of one of these areas-advanced microwave receivers.

DOD Relevance

The DoD has identified total information dominance on the battlefield as a key to overcoming an adversary, with a minimum number of casualties. Information dominance with a totally COTS base is difficult to contemplate since COTS implies that our adversary will have access to all of the system components that we will. Nonetheless, the DoD must leverage wherever possible on the highly-funded, rapid development in the commercial sector. We must use COTS to advantage and yet seek to identify areas of information processing systems where DoD's unique requirements will not be met by the commercial sector and where a modest investment of DoD's very limited resources can provide us with dominant weapon systems.

Summary of Scientific & Technical Issues

The study was carried in three workshops and one field trip.

The first workshop (May 8^{th}) concentrated on identifying broad areas where military information systems might require a non-COTS solution. To this end, we solicited the assistance of a representative of each service and two visionaries in modern information systems. This workshop identified microwave power and advanced microwave receivers as areas where non-COTS solutions might be required. These components are critical in the "see or be seen", cat and mouse game of modern warfare; yet they have no clear commercial counterpart. Radar search depends on radiated power levels as well as receiver sensitivity to the returning pulse in an environment of clutter and jamming. Electronic warfare depends on rapidly detecting hostile emitters and taking possible actions to insure that our forces prevail. Communication, navigation and identification are critical to modern collective warfare where it is has been demonstrated that advanced rapid maneuver tactics employed in disciplined ways can result in successful military action. We selected the Joint Strike Fighter program as a prototype for our discussions.

The second workshop (June 20^{th}) concentrated on the avionics for the JSF. We learned that major cost issues are associated with the avionics suite with the cost approaching more than 40% of the life cycle cost of the system. Mean-time-before-failure (MTBF) is measured in tens of hours adding not only to cost but also time when the system availability. All three of the primary microwave functions, radar, electronic warfare and communications/navigation/identification will require substantial changes in systems architecture to

reduce cost, and increase reliability and functionality. It is envisioned that these changes in systems architecture will require moving the analog to digital boundary in the microwave receiver closer to the antenna so that more of the system can take advantage of high-speed COTS processing. This revolution in architecture will require much capable analog-to-digital converters. Unfortunately analog-to-digital converters have experienced a very slowly developing state-of-the-art. Measuring performance in terms of the number of bits of precision versus the sampling rate, we found that high performance (high sampling rate with a large number of bits) are not represented. Empirically it has been found that the number of bits falls by one bit per octave in the sampling rate. This empirical limit in performance has been moving at the glacially slow rate of 1 bit per 8 years. Analysis shows that this relationship involves the sampling gate timing jitter and quantizer recovery time taken together. Theoretically thermal noise limitations on the number of bits at a given sampling rate lie significantly above the emprically observed limits.

We visited a military-microwave-receiver development group at Hughes Radar Systems to gather some first hand information. We found that current systems are a very complex set of boxes and boards, which have to interoperate precisely. Current major efforts are in the production of retro-fits to fielded systems which are required to increase reliability and serviceability. Improvements due to an advanced receiver would result in major changes in all of the important operational parameters of the systems.

The final workshop (July 25^{th}) concentrated on the design considerations for the receiver. We learned of the challenges that mixed-mode, electronic packaging, filter design and advanced ADC's provided. We found that with adequate developments in filter technology would enhance the employment of COTS ADC's. However, this approach leaves all the difficulties one associates with analog circuits including drift, temperature sensitivity, etc. Analog Devices laid out its plans for COTS which are driven by production volumes that are a minimum of 1 million units per year and typically 1 million units per month. The COTS ADC parts development is driven by commercial customers who are demanding power efficiency at more modest bandwidth. *We determined that serious commitment to COTS only for military microwave systems could result in the following:*

1. *A serious compromise of the performance of the system*
2. *An increase cost by forcing the use of costly/specialized/unreliable analog parts where digital processing could be employed with a non-COTS ADC.*

In addition we learned that recent developments in ADC's could substantially change the rate of improvement in the performance of ADC's. Application of architectures such as $\Delta\Sigma$ which takes advantage of new high speed device technologies such as those based on InP, GaAs, SiGe and perhaps even the InAs/AlSb/GaSb combinations could trade off high speed with low resolution to yield moderate speeds and high resolution at low powers in a flexible programmable ADC's. These improved ADC's could satisfy the ADC needs in many of the retro-fits. Determination of the basic causes of "sampling gate timing uncertainity", thought to be the major limiting factor on the performance of current ADC's could lead to solutions that lower "sampling gate timing uncertainity" and hence increase the number of bits at a given sampling rate.

In addition, there are exciting developments in the use of mode locked laser based sampling and clocking of the ADC's could fundamentally address the sampling gate timing uncertainty issue. Superconductivity provides a possible at the state-of-the-art alternative to

standard semiconductors based approaches even though its requirement for liquid helium (4K) operating temperatures makes it less attractive for deployment in military systems.

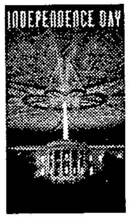
Findings and Suggestions

Summarizing our observations, we observed that:

- A COTS only approach to ADC's will substantially limit advanced military information processing system.
- Emprically current ADC's are "limited" principally by "sampling gate timing uncertainity".
- "Out of the current box" approaches such as optically generated clock and sampling or circuits employing superconductors may be required to overcome the empirical limits.
- Filter were also found to be important but were not included in the study. This topic may warrant further study.

We suggest that:

- Determine origins of the empirical limits and pursue improvements in performance based on that understanding
- Pursue aggressive program in emerging technologies (high count HBT circuits) for high-speed/high-bit ADC's incorporating innovative approaches to circuit design such as incorporating resonant tunneling devices, tunable $\Delta\Sigma$ circuits architectures, etc.
- Pursue alternative "out-of-the-box" technologies to explore the limits of their applicability including superconducting circuits and optically generated clocking and sampling.



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Just in Time Electronics for Weapon Systems

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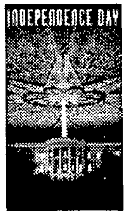

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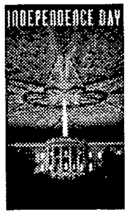
Services

G. Borsuk(Navy)

G. McCoy (Air Force)

B. Perlman (Army)



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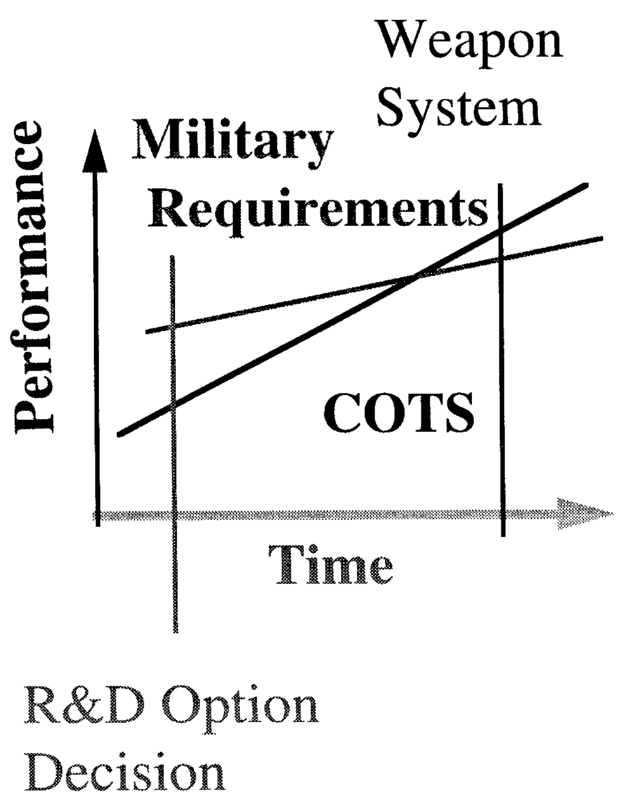
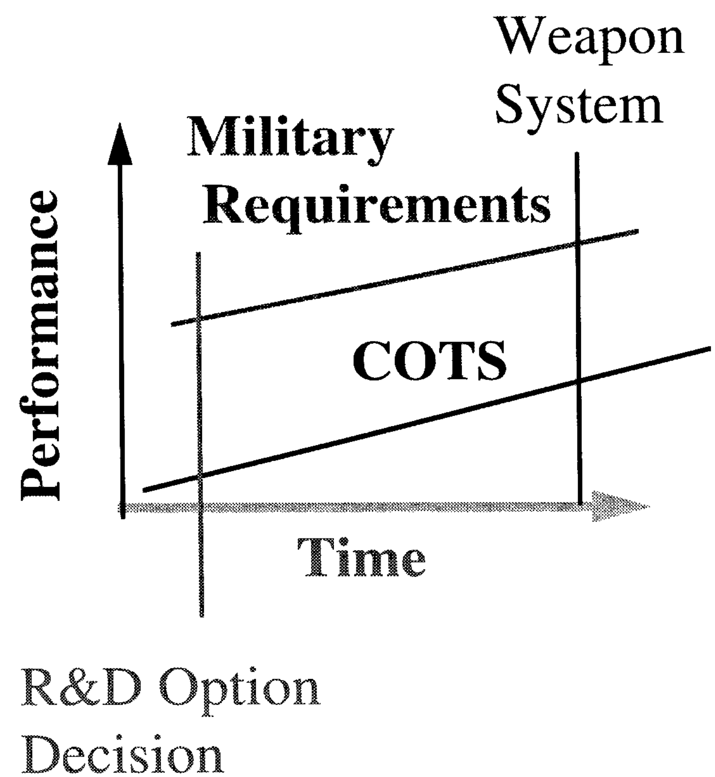
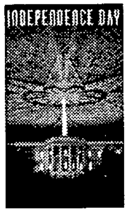
Introduction

- Question of whether all of the electronics needs of the DoD will be fulfilled by Commercial Off The Shelf (COTS)
- Examine Military Requirements and then Decide
- Need Electronics that it is Just in Time for a Required Weapon System
  - Require ten years or more for successes in R&D to be developed into systems
  - Require roughly five years to establish R&D Team
  - Custom Production 2-3 years

Conceptual View







Activities of the Study

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- **3/4/97** — Initation of Study
- **5/8/97** — Workshop to Determine Military Needs
  - Microwave Power
  - Advanced Microwave Receivers
- **6/20/97** — Workshop on Specific Military System (JSF)
  - Advanced Microwave Receiver of Major Importance to Military
- **7/24/97** — Visit to Hughes Radar Systems
  - Advanced Receiver Represents A Very Significant Development
- **7/25/97** — Workshop on Prospects for Advanced Microwave Receiver

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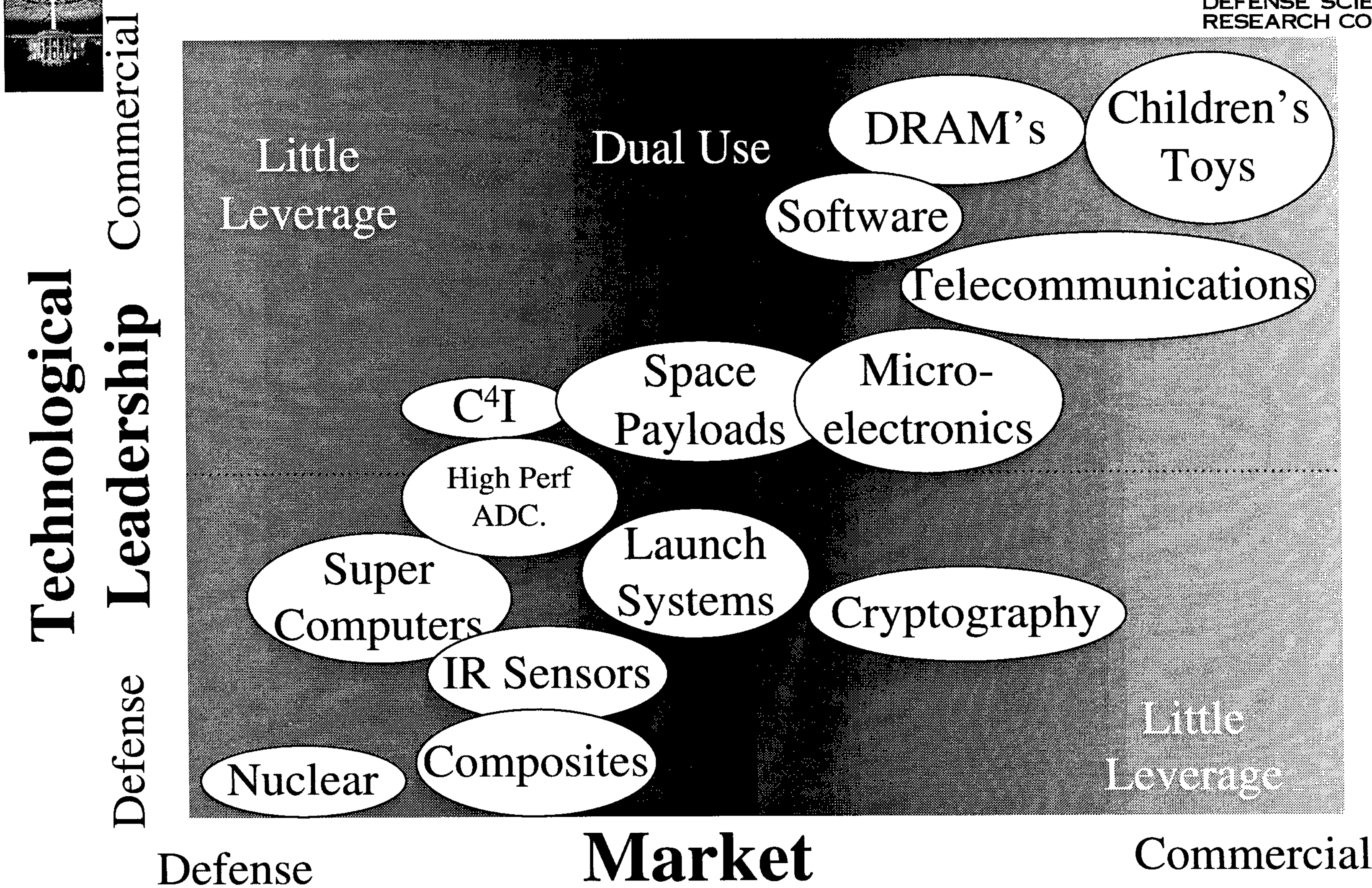

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Summary of May 8th Meeting

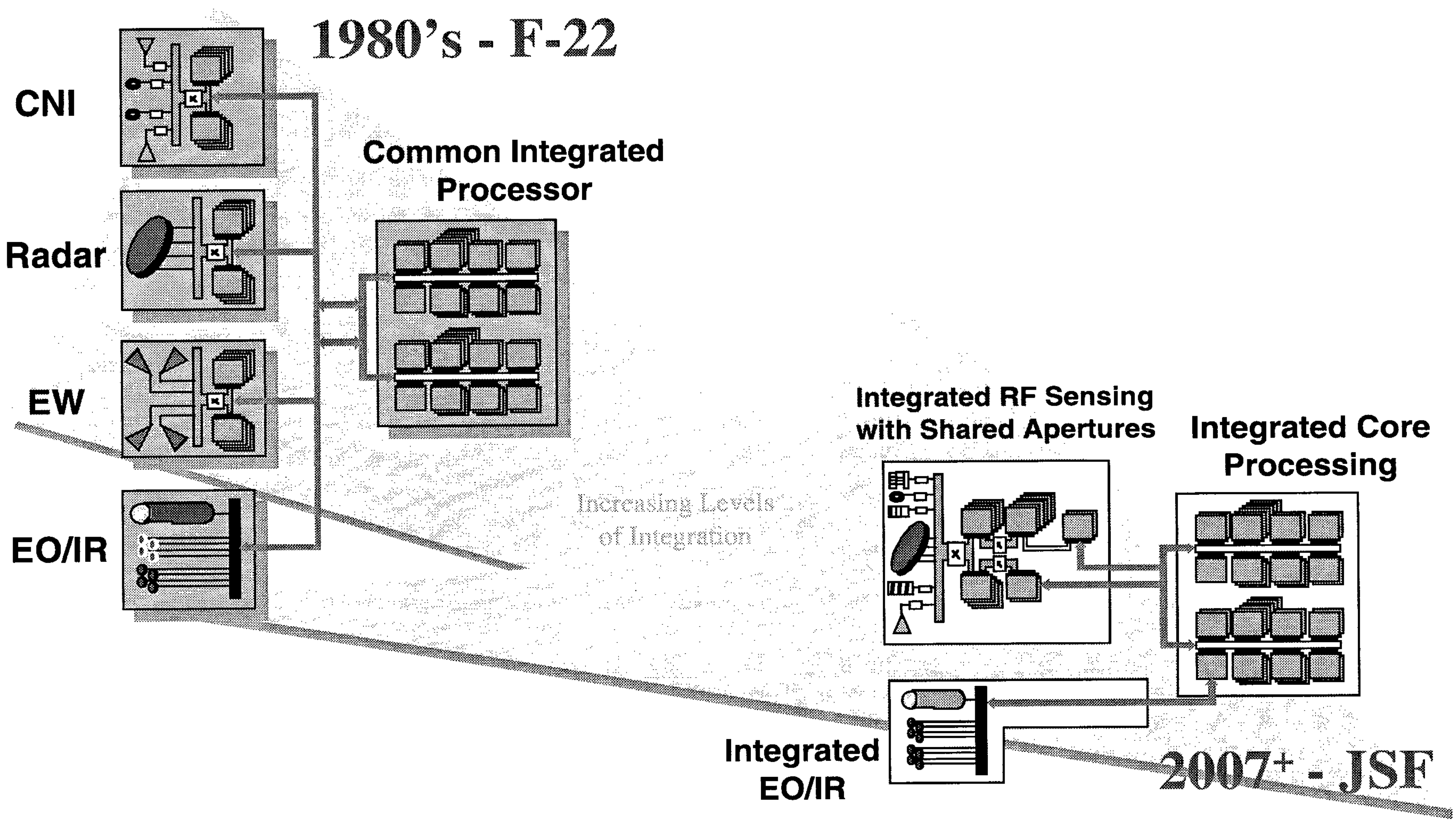
- DoD Must Make Hard Choices about Investment Targets
- Military Will Require Electronics Beyond COTS
  - High Power Microwave
  - ADC's for Microwave Receivers

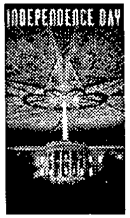
Joint Strike Fighter Program

VISION

"A Joint Services Team creating the building blocks for affordable, successful development of next generation strike weapon systems."

Components of an Integrated Avionics Suite (Mark Minges (AF)





Major Opportunity

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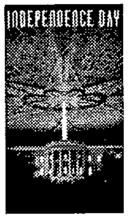
- Digital Electronics is Providing The Major Opportunity of the Late 20th Century
- COTS Usage Depends on Getting Analog to Digital As Soon As Possible
  - Most Signals are Analog
  - Become Digital by ADC
  - Digital Signal Processing Versatile and Inexpensive



Microwave Receiver

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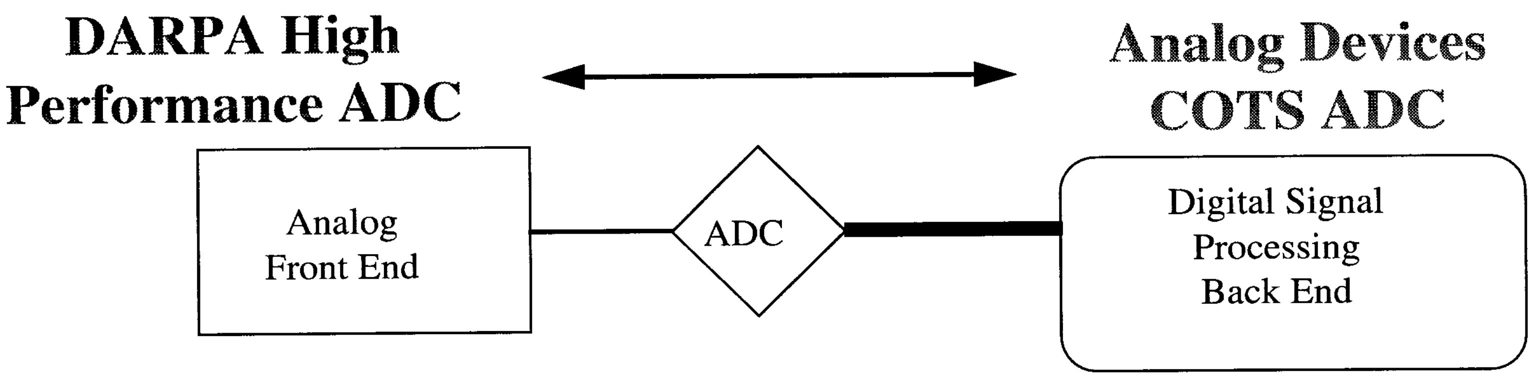
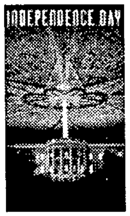


- Performance of ADC Determines Boundary
  - Lower Performance of ADC's Requires More on Analog Front End
- Desirable to Move Boundary So Everything in Software in Signal Processor
  - Lots of COTS
  - Lots of Flexibility



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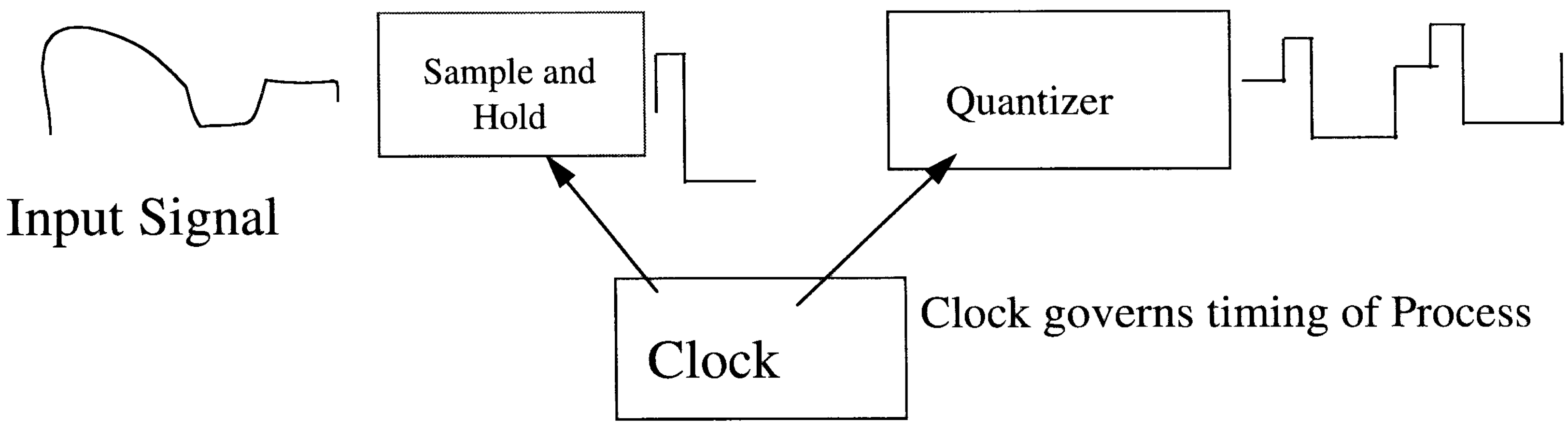
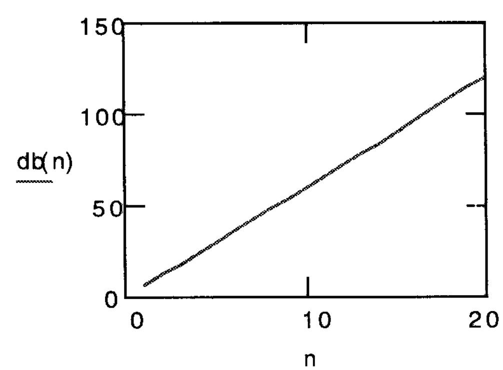
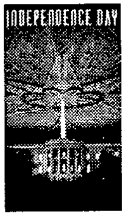
Anatomy of ADC Process



$$db = 20 \log_{10}(2^n)$$



Sampling Rate = 2 x (Maximum Frequency)



Analog-to-Digital Converter Data: Stated Resolution (Walden Plot)

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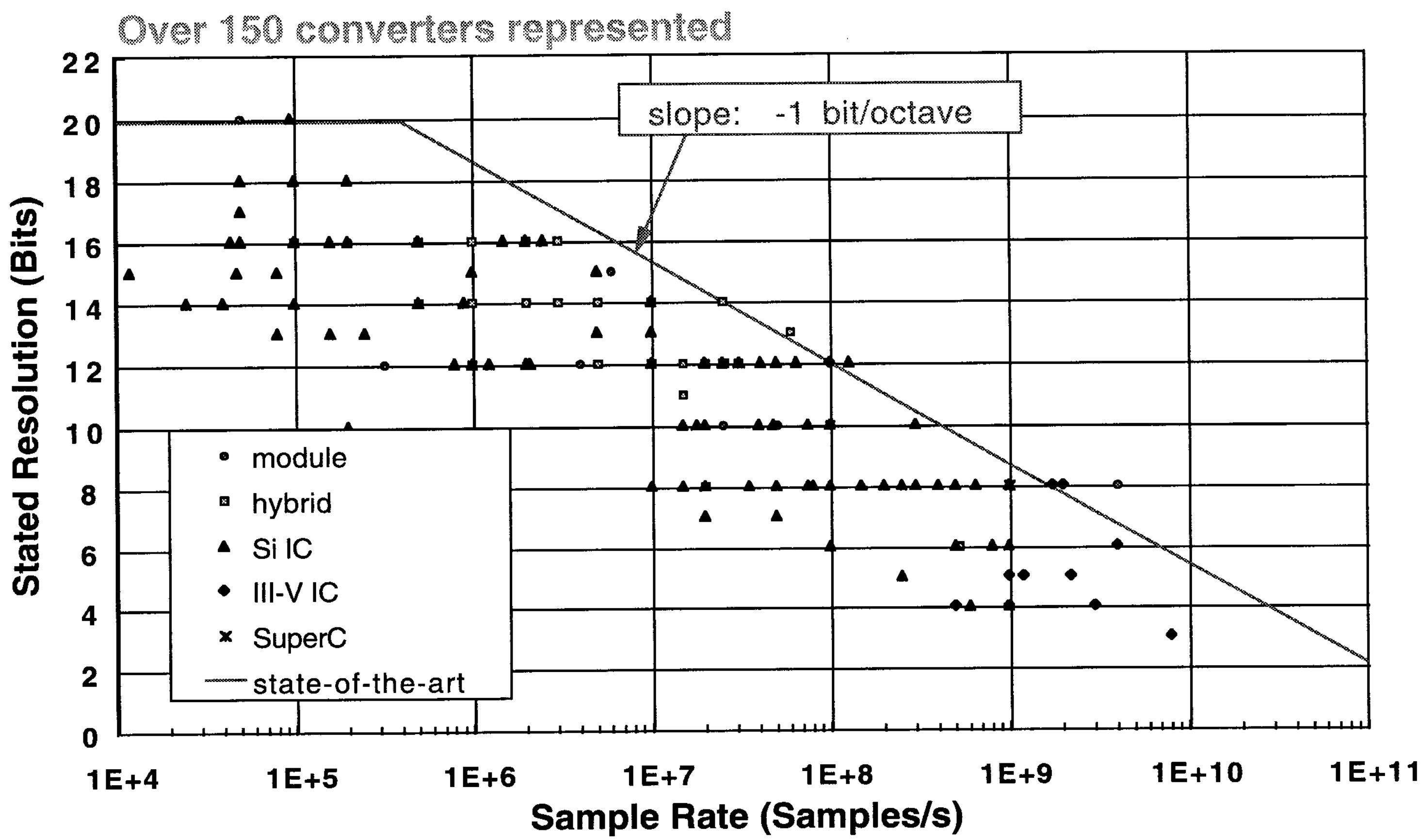
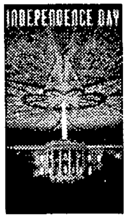
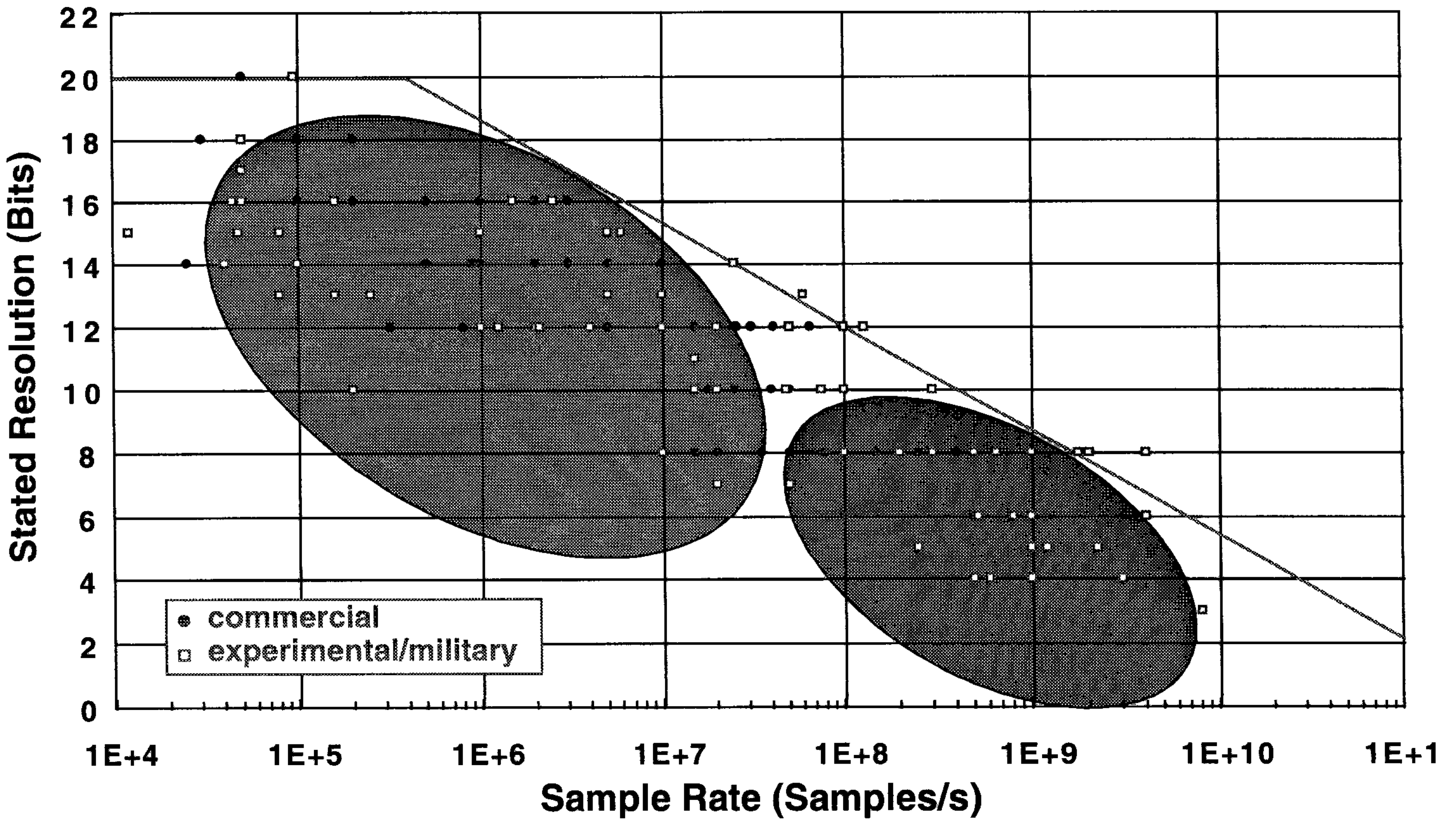


Analog-to-Digital Converters: COTS / non-COTS





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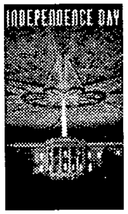

ADC Performance Limitations

Basis: Signal-to-Noise Ratio

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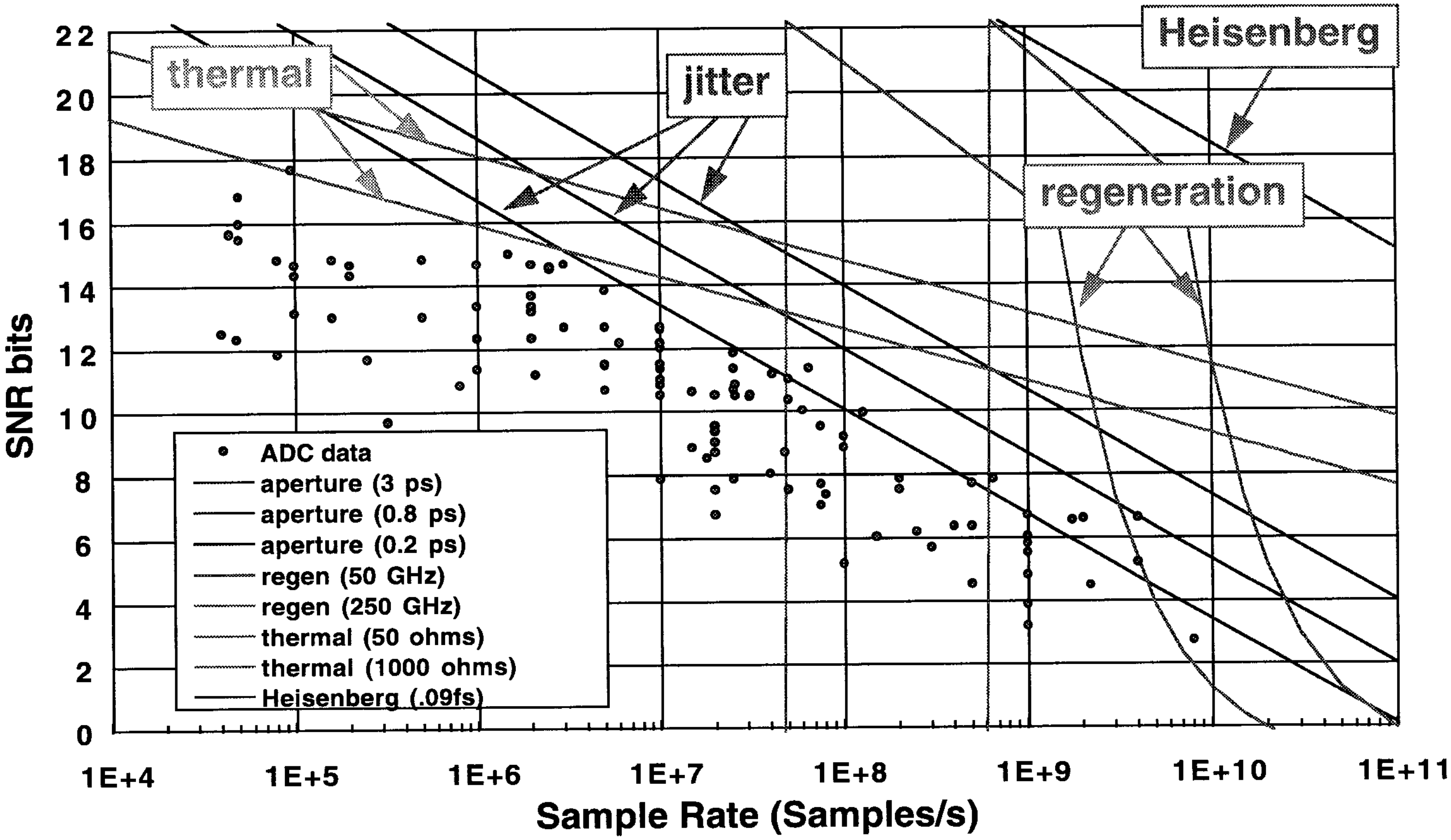

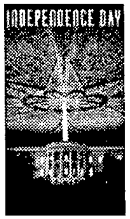

Summary of Walden Observations

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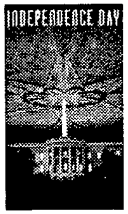
- Empirical Number of bits versus sampling rate indicates that there is defined boundary (a Wall) in ADC Performance
- The COTS ADC's are at Lower Performance Levels than the military developed ADC's
- "Clock Jitter" seems to be the Likely Cause of the "Wall"
- The "Wall" Moving Very Slowly Roughly 1 bit every 8 years



ADI VIEW OF COTS

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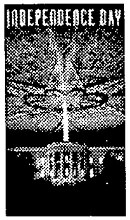
- ADI supports the view that military systems should be configured to utilize commercial products within their guaranteed performance and environmental specifications.
- We caution against using commercial products outside of the range for which the products are designed.
  - Performance range.
  - Environmental range: Temp/Radiation.



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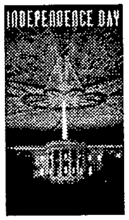
Market Drivers for High Speed Converters
The ADI Perspective

Consumer:

- Going Digital: Voice, Audio, Imaging, Video
- Cheaper
- Portable: Low Power
- Small Size: Integration

Communications:

- Gone Digital
- More Capacity: voice-data-image-video
- More Spectral efficiency
- Replace Analog Processing with Digital
- Smaller, Cheaper, Lower Power



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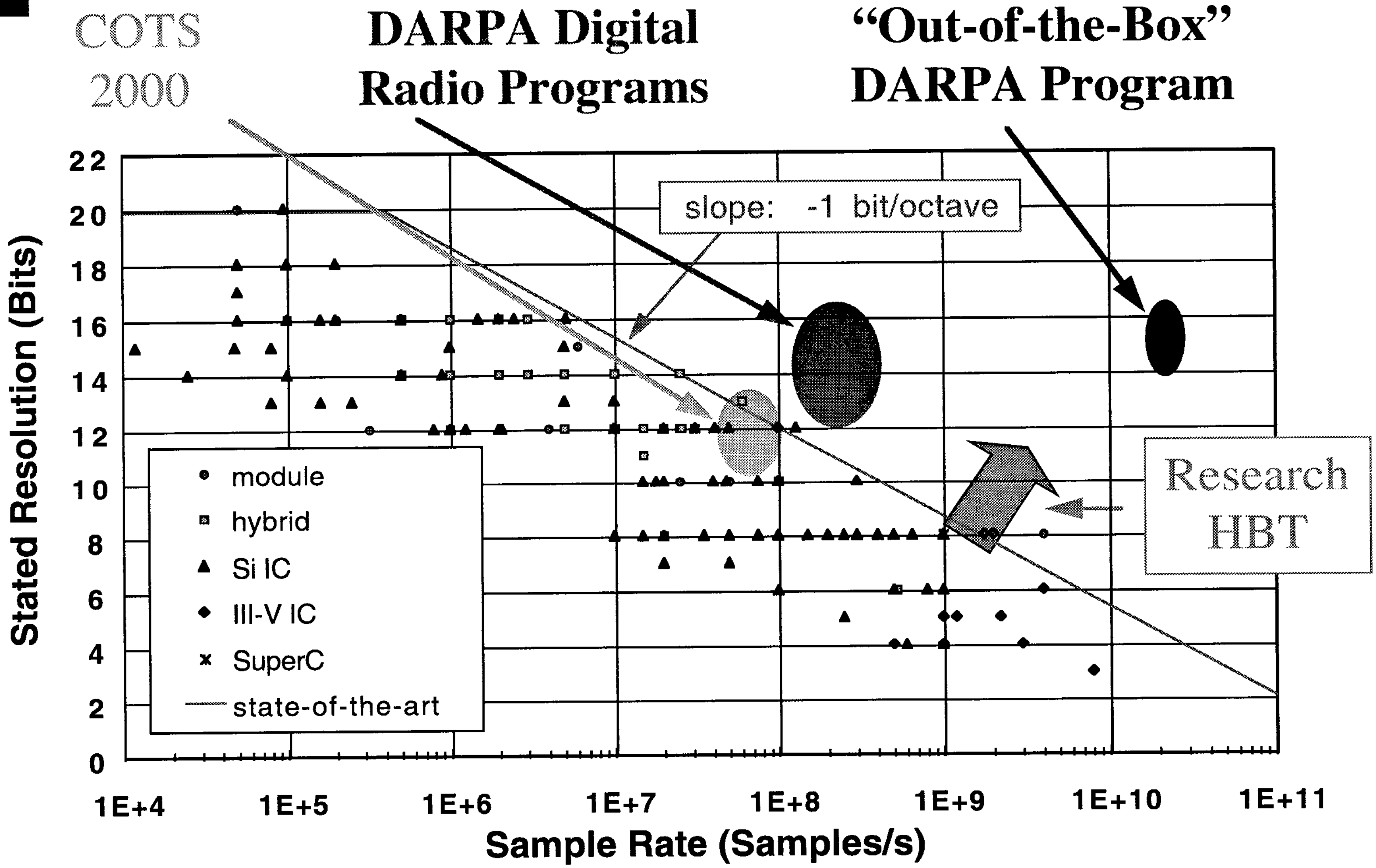
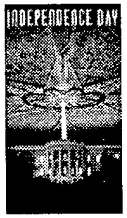
Walden Plot





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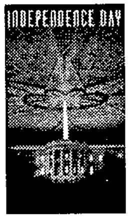
WILL COMMERCIAL INDUSTRY SUPPLY ALL ELEMENTS FOR THE ELECTRONIC SYSTEMS WHICH WILL DOMINATE NEXT GENERATION WARFIGHTING CAPABILITIES?

Barry K. Gilbert
Special Purpose Processor Development Group
Mayo Foundation

NO!

The following are examples of major system capabilities of <u>revolutionary</u> importance to the DOD which are unlikely to be developed by commercial industry.

Each major capability requires specific low-level technologies, or special technology directions, which will not be undertaken by commercial industry



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Gilbert (Cont'd)

The U.S. through DARPA/DOD, has made large investments in military research and development for decades, leading to significant military capabilities

The U.S. needs to continue making such investments to guarantee an ongoing military advantage

The U.S. is rapidly "eating its seed corn", the technology reserves built up during the 1960s-1980s

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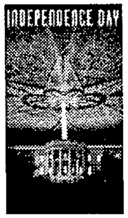
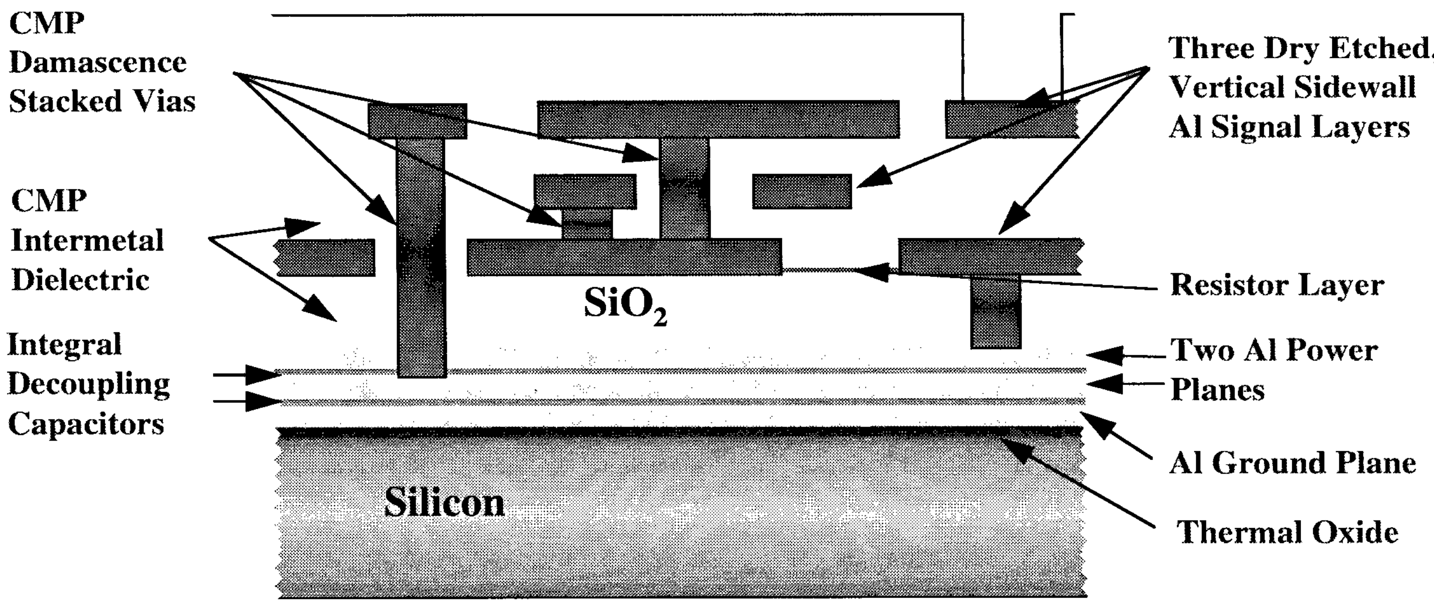
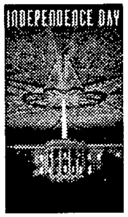


INCREASED ELECTRICAL PERFORMANCE OF ELECTRONIC PACKAGING THROUGH IMPROVED MANUFACTURING PROCESSES: COMPLETE CONTROL OF METAL AND DIELECTRIC STRUCTURES, SHAPES, THICKNESSES, AND PROPERTIES





Possible Size Reductions with Advanced Multi-function InP Technology

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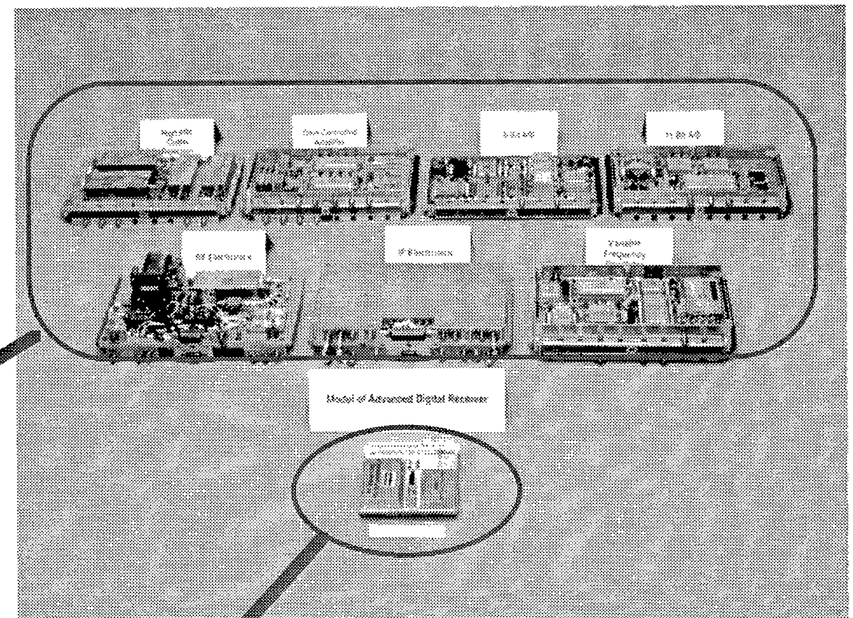
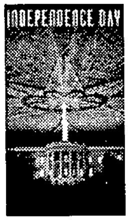
- Size Reduced By A Factor Of 10.3
- Weight Reduced By A factor Of 7
- Cost Reduced By A factor Of 10
- Power Consumption Reduced By A Factor Of 9.8

* Comparison of an advanced receiver with InP front end/ADC chip to equivalent F-15 APG-63(v) receiver and housekeeping functions



Current Production
Two Channel F-15
Radar Receiver
Seven Module Set

Advanced Digital
Receiver
Single Channel
Module



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Truly DARPA

- Major Technology Breakthroughs Required
- Will Enable
  - Higher Performance
  - Cheaper
  - More Flexible Systems

Technologies for ADC Applications (HRL)

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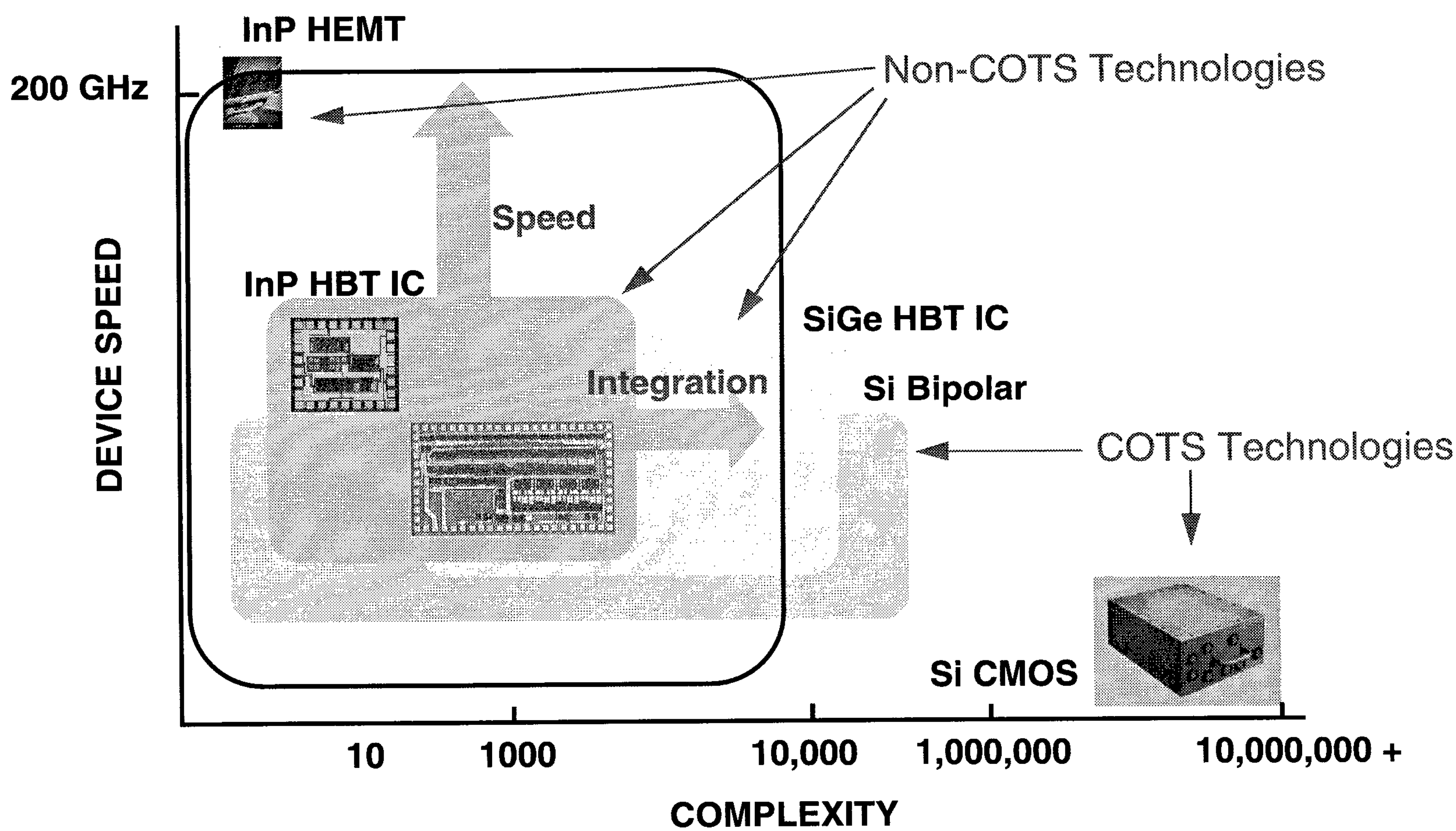

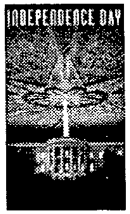

Resonant Tunneling Devices (Raytheon/TI and HRL/Mayo)

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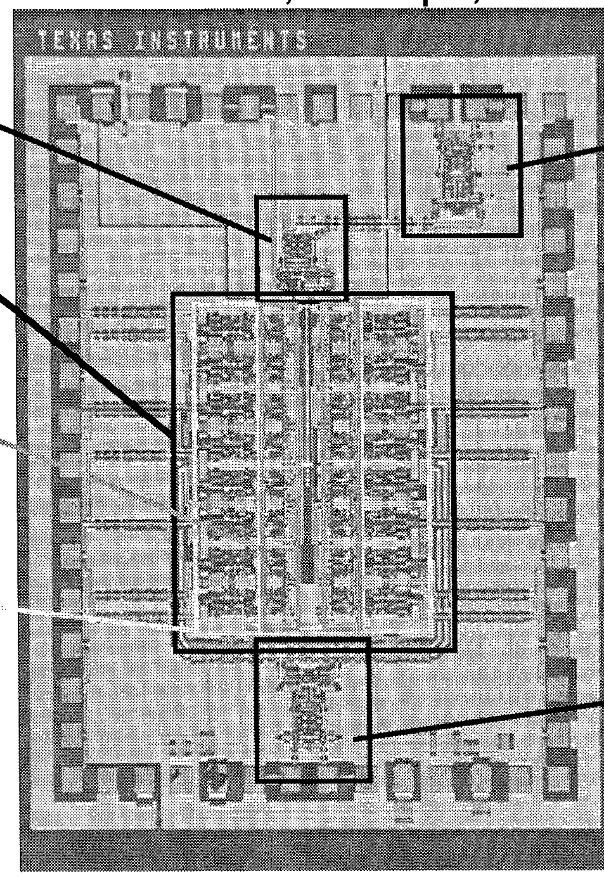
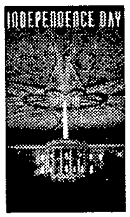
- Gives Very High Speed Switch to Use in Quantizer.
- Could Make Substantial Decreases in
  - Part Count
  - Power Consumption

4 Bit, 3 GSps, 810 mW



InP HBT/ RTD's



Optical Sampling (LL)

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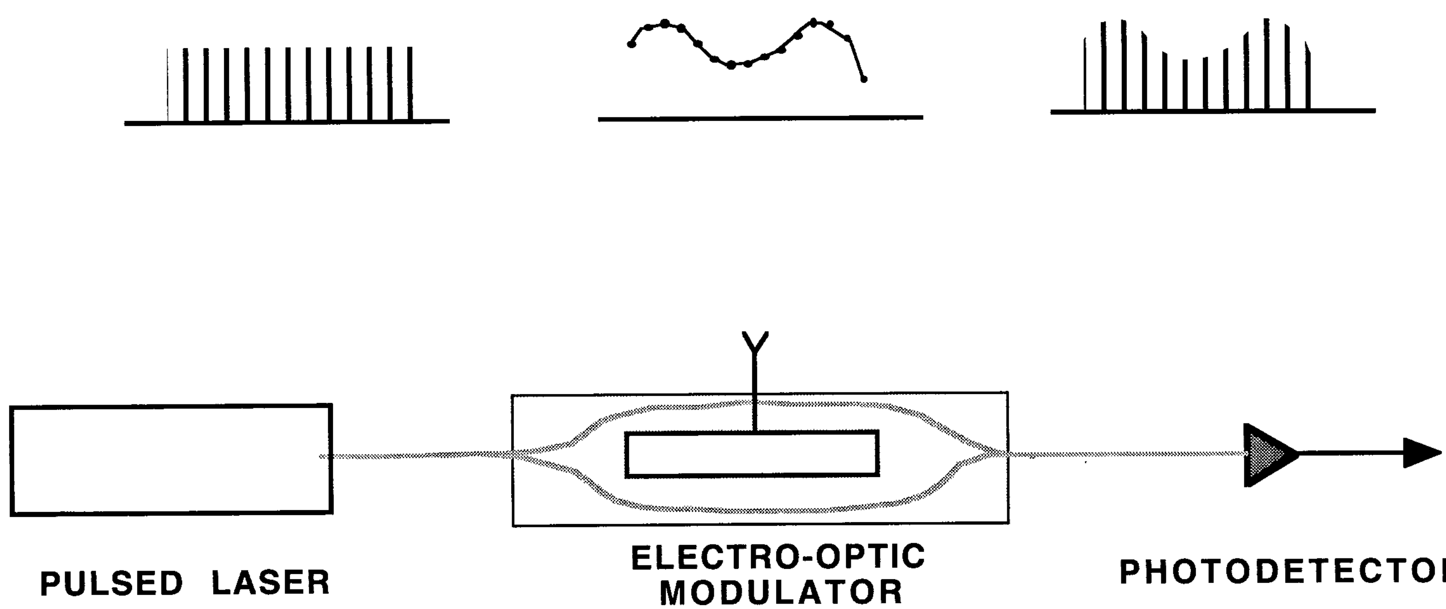

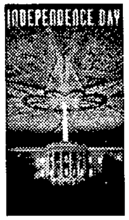

Proposed Optically Sampled A/D (LL)

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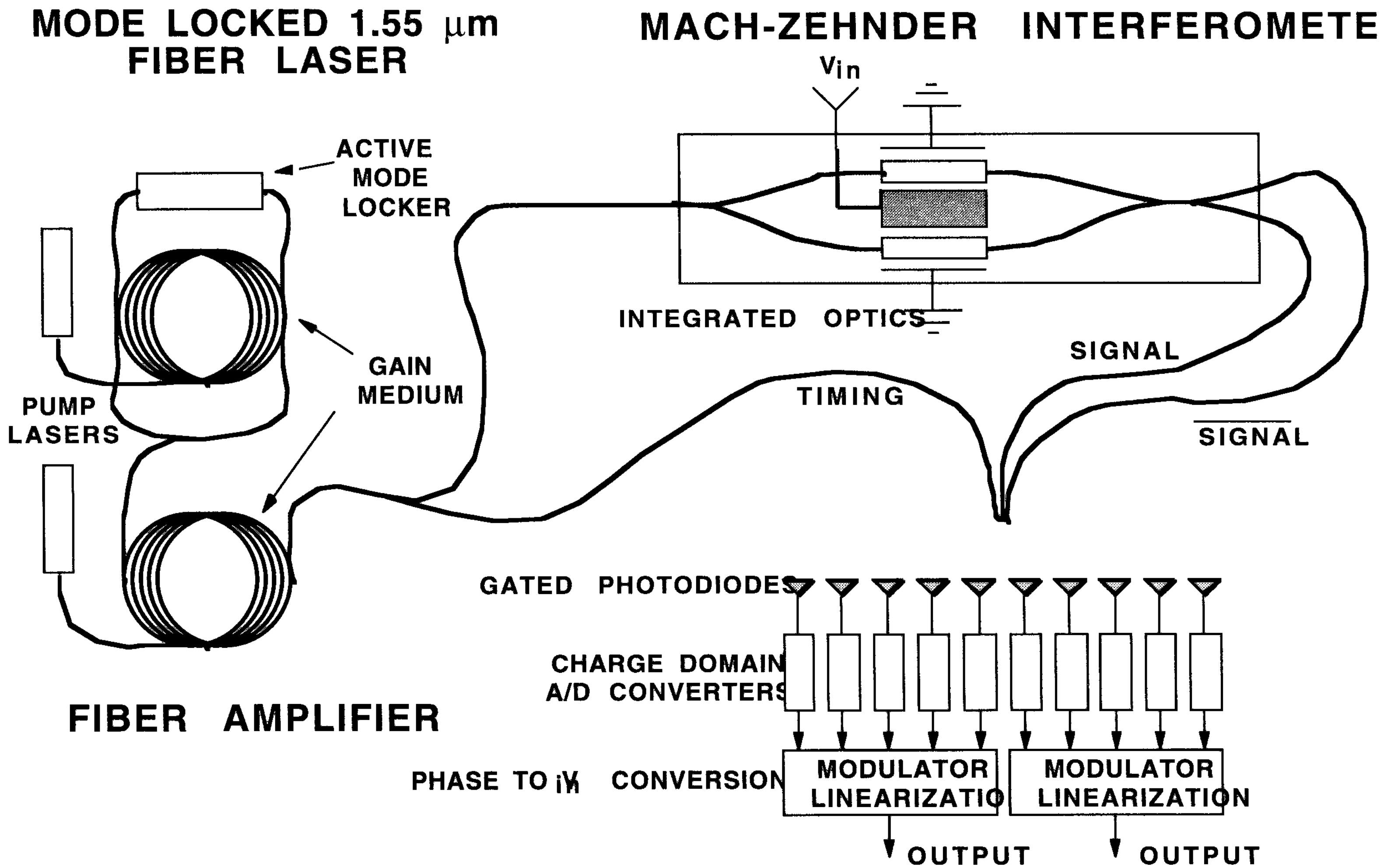

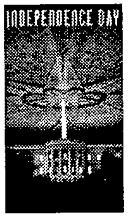

Flash ADC: High-Speed Results (Hypres)

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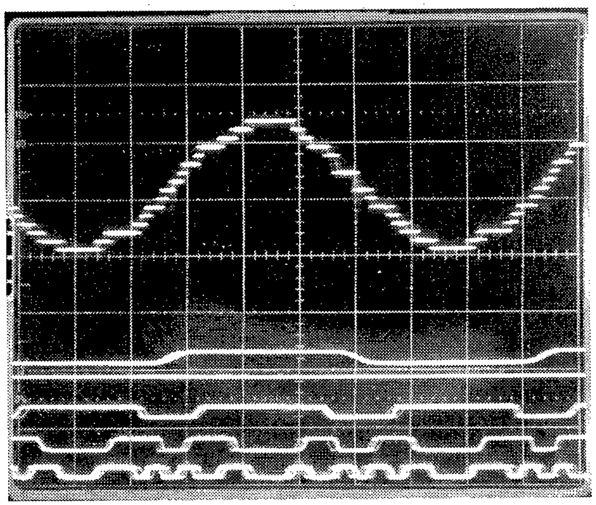
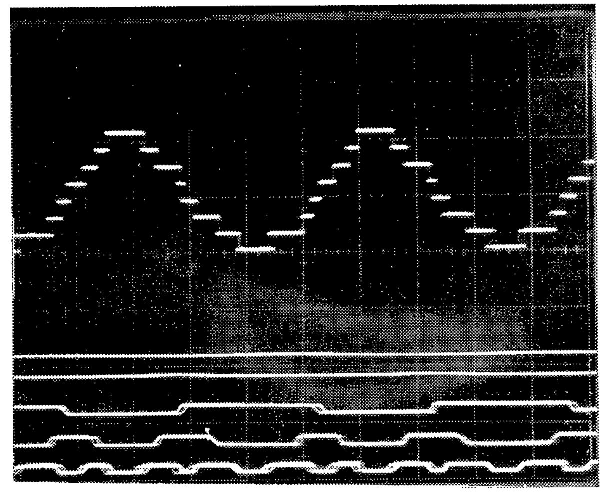
Beat-Frequency Tests with Signal Reconstruction



12.000001 GHz Signal
12.000000 GHz Clock

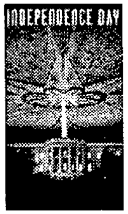


19.999995 GHz Signal
20.000000 GHz Clock

With digital error correction no errors would be visible

Interleaving will produce even higher resolution (6 bits at 20 Gs/s)

Temperature=4.2K but High Tc Superconductors Coming



Findings

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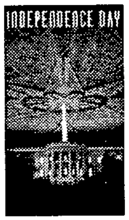
- A COTS only approach to ADC's will substantially limit advanced military information processing system.
- Emprically current ADC's are "limited" principally by "sampling gate timing uncertainity".
- "Out of the current box" approaches such as optically generated clock and sampling or circuits employing superconductors may be required to overcome the empirical limits.
- Filter were also found to be important but were not included in the study. This topic may warrant further study.



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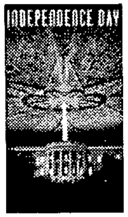
Suggestions

- Determine origins of the empirical limits and pursue improvements in performance based on that understanding
- Pursue aggressive program in emerging technologies (high count HBT circuits) for high-speed/high-bit ADC's incorporating innovative approaches to circuit design such as incorporating resonant tunneling devices, tunable $\Delta\Sigma$ circuits architectures, etc.
- Pursue alternative "out-of-the-box" technologies to explore the limits of their applicability including superconducting circuits and optically generated clocking and sampling



Agenda (May 8, 1997)

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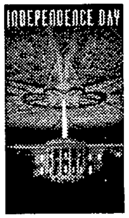
Time	Item
0800-0830	Coffee and Administrative
Kickoff Discussion	
0830-0915	DARPA Perspective-Lee Buchanan, Ken Gabriel, Anis Husain (?) Fabian Pease
0915-0930	Discussion
Warfighter Perspective	
0930-1015	Navy Needs-Gerald Borsuk (NRL)
1015-1030	Break
1030-1115	Air Force Needs-Gary McCoy (AFWP)
1115-1200	Army Needs-Barry Perlman (Ft. Monmouth, NJ)
1200-1245	Working Lunch (Discussion of Service Needs)
Weapons Provider	
1245-1345	Perspective of a System Planner-Barry Gilbert (Mayo)
1345-1400	Discussion
1400-1445	Perspective of device/subsystem developer-David Shaver (LL)
1445-1500	Discussion
1500-1515	Break
1515-1700	Prioritization and Preparation for Discussion with COTS Vendors



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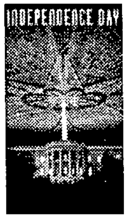
Agenda for June 20th Meeting

Time	Item
0800-0830	Regroup
Systems Issues	
0830-1000	Overview Briefing on JSF Multi-Purpose Single Aperture System with an Emphasis on Hardware Specifications and Possible Sources of COTS Hard- Chris Evans (JSF Program Office)
1000-1015	Break
1015-1200	Technical Requirements for ADC's for Digital Microwave Receivers-Scott Rodrigue, Emil Martinsek, and Mark Minges (AFWL)
1200-1300	Working Lunch-Semiconductor Based ADC-Bob Walden (Hughes)
1300-1500	Regroup and where do we go from here.



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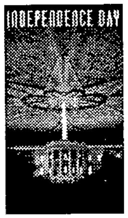
Agenda (July 25th Meeting)

Time	Item
0800-0830	Report on Meeting in Washington-T. C. McGill
0830-0915	Challenges of Mixed Mode Systems-B. Gilbert (Mayo)
0915-1000	ADC's Architectures and Issues-R. Walden (HRL)
1000-1015	Discussion of Issues
1015-1030	Break
1030-1115	COTs Can Do It-Dennis Buss (ADI)
1115-1200	Receiver Architectural Design Issues-J. Brewer(Northrop Grunman)
1200-1230	Lunch
1230-1255	RTD's for ADC's-Alan Seabaugh(TI)
1255-1315	Advantages of Digital Signal Processing with Sb Based Devices-David Chow (HRL)
1315-1345	Optical Gating for ADC's-Dr. Jonathan Twichell (Lincoln Labs)
1345-1415	SuperConducting Approaches to ADC's-Dr. Elie Track(Hypres)
1415-1445	Systems Implications of Advanced Device Technologies for A/D's-Joe Jensen(HRL))
1445-1500	Break
1500-1600	Formulation Recommendations



The Filter Challenge (Northrop-Grunman)

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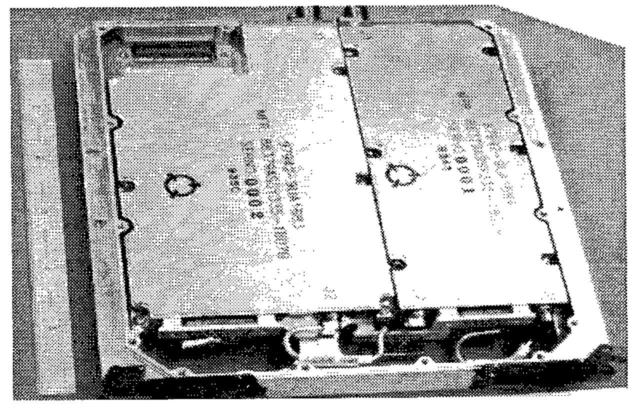
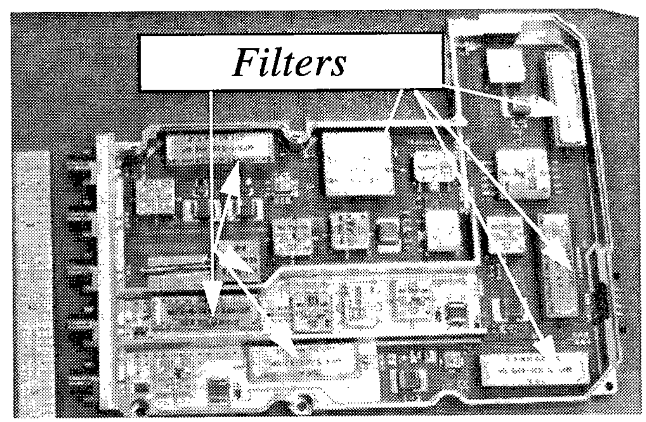
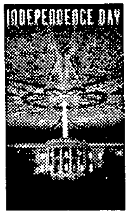
- Filters dominate receiver weight, volume & cost
- Typical radar system contains >100 Filters
- Filters are used across a broad frequency spectrum
- Typical LRM has 20-30% volume devoted to filters (One is 80% Filters)







Miniature Filter Technology (Joe Brewer (Northrop Grunman)

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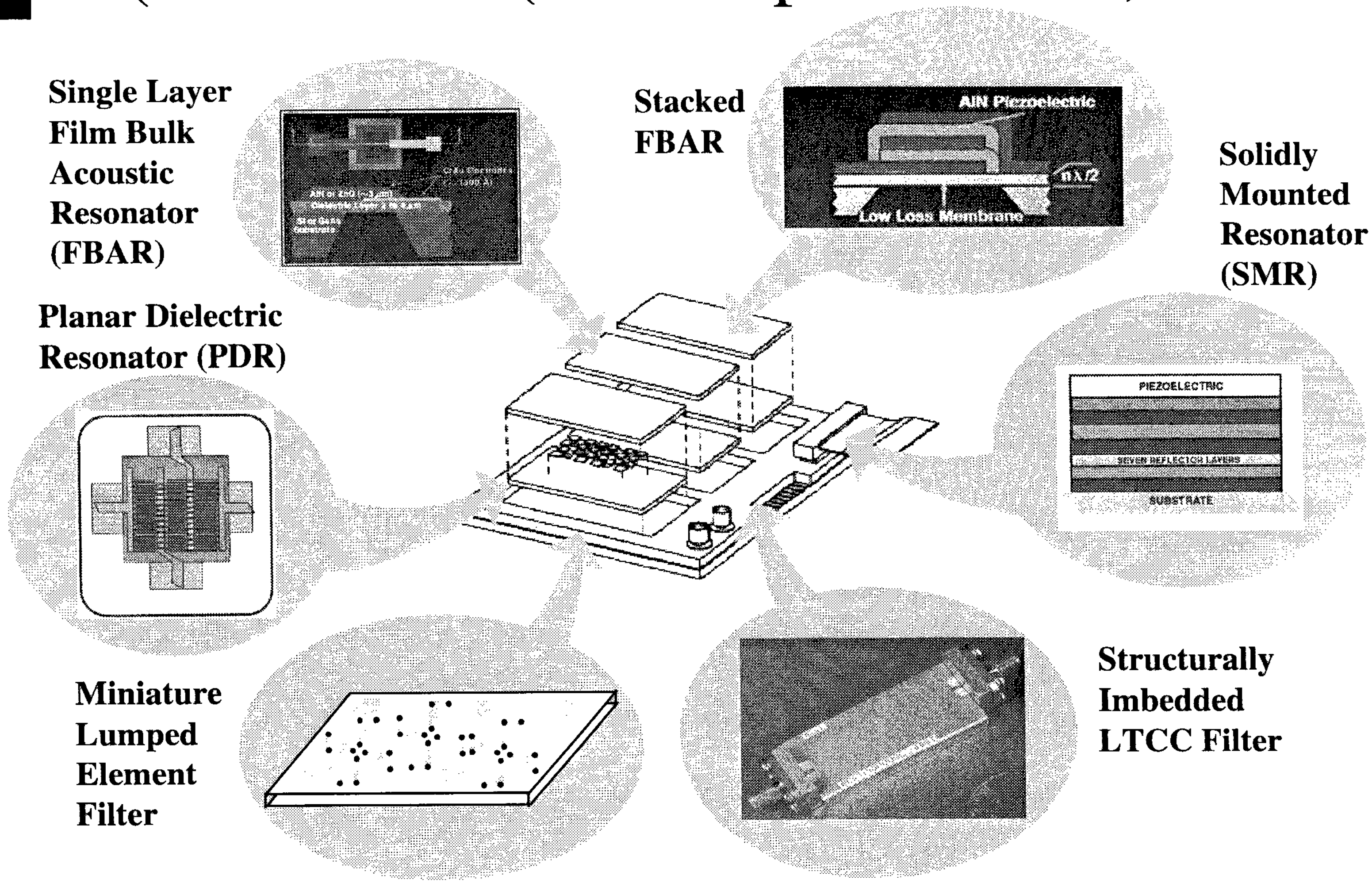

JUST IN TIME ELECTRONICS FOR WEAPONS SYSTEMS

Workshop Organizers: T. C. McGill and R. M. Osgood

Friday, July 25, 1997

8:00 a.m.	**Report on Meeting in Washington** Tom McGill (DSRC)
8:30 a.m.	**Challenges of Mixed Mode Systems** Barry Gilbert (DSRC)
9:15 a.m.	**ADC's Architectures and Issues** R. Walden (HRL)
10:15 a.m.	**Break**
10:30 a.m.	**COT's Can Do It** Dennis Buss (ADI)
11:15 a.m.	**Receiver Architectural Design Issues** J. Brewer (Northrup Grumman)
Noon	**Lunch**
12:30 p.m.	**RTD's for ADC's** Allen Seabaugh (TI)
1:00 p.m.	**Advantages of Digital Signal Processing with Sb Based Devices** David Chow (HRL)
1:15 p.m.	**Optical Gating for ADC's-Z** Z. Lemnios
1:45 p.m.	**Superconducting Approaches to ADC's** M. Beasley (DSRC)
2:15 p.m.	**"Standard Device" Approaches to ADC including SiGe, GaAs InP HBT's** P. Greiling (HRL)
2:45 p.m.	**Break**
3:00 p.m.	**Formulation Recommendations**

JUST IN TIME ELECTRONICS FOR WEAPONS SYSTEMS

Friday, July 25, 1997

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COMBINATORIAL AND/OR COMPUTATIONALLY GUIDED SYNTHESIS OF NEW MATERIALS

F. DiSalvo, H. Ehrenreich, and M. Beasley

EXECUTIVE SUMMARY

Objective

Critically examine the possibility of speeding up (by orders of magnitude) the discovery, optimization and development of new and useful materials.

DOD Relevance

Many DoD systems are limited by materials performance or by lack of any material to meet a recognized need (e.g. thermoelectric cooling devices). Current methodology is largely a one-at-a-time preparation of modified or new materials. A more efficient process could greatly impact the ability to meet DoD needs in new materials.

Summary of Scientific & Technical Issues

Parallel synthesis of large "libraries" of samples, each of differing composition, can processed to produce products whose properties vary slowly across the library. By constructing library sequences, the property can be optimized as a function of composition and processing conditions. This approach could speed up the discovery/optimization process by a thousand fold or more. Development of parallel synthesis machines and characterization tools has begun at a start-up company (Symyx) and at LBL, but these are not generally available. Computational tools could also be developed to guide the choice of materials or compositions, but a useful implementation of this approach is especially challenging. More rapid implementation of both experimental and computational techniques could be spurred by choosing specific targets of opportunity of interest to DoD. For initial development it may be advantageous to choose materials and phenomena that are not very sensitive to impurities and /or defects.

Conclusion and Observations

No fundamental barriers to implementing parallel synthesis and characterization schemes are apparent. Development of instrumentation to efficiently prepare materials libraries and characterize the products is needed. Presently such instrumentation has been developed and is in use at Symyx and LBL. Many materials systems of potential DoD interest could benefit from the approach, but instrumentation is not available to the broad materials community. Direct collaboration with the developers may be possible in some cases.

The grand challenge to the theoretical community is to provide input into choosing materials systems and specific compositions <u>on a timely basis</u>. Much stronger interaction with the materials synthesizers, even producing software tools that experimentalists could use, is needed. On a grander scale, understanding what is necessary to predict the structure of new materials and when it can be done with confidence would be even more helpful, but this challenge is indeed formidable.

COMBINATORIAL AND/OR COMPUTATIONALLY GUIDED SYNTHESIS OF NEW MATERIALS

Organizers: F. DiSalvo, H. Ehrenreich, and M. Beasley

Workshop Objective

Critically examine the possibility of speeding up (by orders of magnitude) the discovery, optimization and development of new and useful materials.

DoD Relevance

Many DoD systems are limited by materials performance or by lack of any material to meet a recognized need (e.g. thermoelectric cooling devices). Current methodology is largely a one-at-a-time preparation of modified or new materials. A more efficient process could greatly impact the ability to meet DoD needs in new materials.

Scientific and Technological Summary

The current methodology of discovering and optimizing materials with novel and/or useful properties is to synthesize and examine them one at a time (or at best in small batches of a dozen or so), as a function of composition, processing conditions, etc. Since the size of the materials synthesis community is unlikely to grow substantially, a considerable increase in the rate of discovery/optimization requires a new approach. The concepts of combinatorial synthesis (or massively parallel synthesis) may be what is needed. Further, advances in both theoretical models and algorithms as well as in computer power and access suggest that computational methods usefully guide the search for new and/or optimized materials.

To address the challenges in both combinatorial and computational approaches a Workshop was convened in Arlington, VA on June 25. The 25 attendees (4 from DARPA, 6 from DSRC and 15 other experts in synthesis, characterization and data bases, and condensed matter theory) considered and discussed presentations by 5 participants. Several of the participants had connections to Symyx Co., a small start-up company in Silicon Valley that was set up to exploit combinatorial synthesis of polymeric and inorganic materials. Many of the attendees were initially skeptics concerning the feasibility of such approaches. After the presentations, breakout groups considered specific challenges, state of the art, and possible progress in the next 5 to 7 years in three areas: synthesis, computation and characterization. Questions considered by each group included:

- What is the state of the art now?
- What are scientific and technical barriers to implementation?
- Can these barriers be overcome in 5 –10 years? At what level of effort?
- What specific materials/properties should be targeted? DoD relevance?
- Can and how can experiment and theory be coupled?

At the conclusion of the Workshop, there was a high level of enthusiasm and optimism that the parallel synthesis approach will be an important methodology in the near future. The prospects for theoretical contributions to this effort are more circumscribed but still contain considerable promise, especially in the longer term. A more intimate relationship

between theorists and synthesizers will have to be developed, however, for the potential to be realized. Details and specific challenges are discussed below. Experimental approaches are discussed first, then computational methods.

Synthesis:

Researchers at Lawrence Berkeley Laboratories (LBL) and at Symyx Corp. have already demonstrated in several materials systems that a parallel approach can be implemented. The first method developed is a thin film technique using a series of masks to sequentially deposit different elements in different "pixels" on a single substrate. Substrates (sometimes referred to as "libraries") containing up to 10,000 pixels, or different compositions, have been prepared. These multilayer samples are then reacted at elevated temperatures in controlled atmospheres. Many wafers could be reacted at once in uniform environments or in processing "gradients". Depending upon the particular materials system, the automated deposition of reactants may be accomplished in a number of ways, including: evaporation (or sputtering, so- and gradient deposition, etc.), metering of solutions or dispersions into micro-reaction vessels, gas flow reactors, etc. Such methods could also be applied to the synthesis of polymeric systems, but we explicitly limited our discussions to inorganic, extended structure materials. While there are many experimental challenges, such as substrate reactivity, film stress, potential impurity or doping problems in very small samples, and multiple phase formation, no insurmountable difficulties were identified in the synthesis approaches. However, the methodology is sufficiently different from that currently extant that practitioners will need to develop or purchase special apparatus to prepare the libraries – or to collaborate with those that have such available.

In the long term we expect that this approach will:

- Lead to new synthetic principles (e.g. understanding and controlling complexity in structure and composition of single phase materials)
- Make practical multi-step routes to synthesis and to multi-functional materials
- Accelerate discovery of new materials (including metastable phases) and of new or improved behavior

Other observations include:

- For new materials/phenomena, an existence proof is good enough to attract.appropriate interest; negative results do not prove non-existence
- For materials optimization, it is important to be close to real processing conditions and perhaps even sample size, in order to avoid effects of "hidden " variables
- Processing under either kinetic or thermodynamic control should be possible
- Best informatic approach to libraries is not clear – both in library design and data storage/dissemination. Need to minimize relearning.

Characterization:

An obvious challenge with massively parallel synthesis is the need for rapid characterization of.the library just synthesized. In some cases only a single or few properties will need to be measured, while in others it may be advantageous to characterize each pixel as completely as possible. Such measurements must be rapid and easily digested, or the whole parallel synthesis method would be limited by a characterization bottleneck. Obviously the best

characterization methods will also be parallel and scalable to large arrays. Again, work at Symyx and LBL has demonstrated that some measurements are easily adapted to parallel methods using current technologies, while others need development. However, no fundamental technological barriers could be foreseen.

Property Measurement Techniques :

1. Optical – ideally suited to rapid scan techniques using CCD technology. Any "property" that directly or indirectly produces an optical signature (emission, temperature difference, Faraday rotation, etc.) is ideally probed in this way. Assuming a measurable signal, it is very fast, massively parallel, and outputs are easily visually displayed. Already used at Symyx. Challenge: finding optical signatures of a larger number of properties of interest.

2. Electromagnetic (rf and microwave frequencies). Best done in a contactlessmode but can.be done with electrical probes. Spatial resolution and parallel operation is currently a challenge when 1000 or more pixels are to be probed.

3. Mechanical – little explored in the current efforts. MEMS devices (parallel STM, AFM, microindenters, etc) could be developed to scan surfaces of libraries. Some mechanical properties could be obtained in this manner. In film systems, mechanical properties may be affected by the substrate and may not reflect bulk behavior.

4. Chemical and Structural Characterization: again not well developed for libraries of samples. Most embodiments imagined would be serial, one pixel at a time. May be most useful as a second screening step when some other property of the pixel appears interesting.

Cautions: In most inorganic systems single phase products will be produced only at a few specific and definite compositions. At any other composition the thermodynamic products will be multiphase. Also, under specific processing conditions, the products may be metastable, which may or may not be desirable. In any case, the measured properties of a multiphase pixel may be irreproduceable, difficult to interpret, or may even depend upon the particular microstructure of the sample. On the other hand, in certain situations, such as searching for a high T_c superconductor, multiphase samples may be advantageous – even more composition/ structure types may be examined at once with more refined screening in a second step.

Computation:

Many methods have been developed to calculate the properties of solids, once the composition and structure are known. These calculations are based on inexact models, however, and thus judgement in their use is required. Simple properties can be computed with useful reliability using methods such as LDA and GW techniques. However, such calculations are very intensive computationally, even with the massive and fast computers now available. Further, the number of atoms per unit cell is limited by memory size – even in the largest machines. Finally, when one is interested in the properties of new materials, the resulting composition and crystal structure cannot usually be predicted, unless the material is a simple derivative of one that is known. At present it is virtually impossible to calculate the equilibrium structure of a complex material. Some empirical methods are capable of systematizing what is known, at filling in "vacancies" of potential structures, etc., but none can presently predict new structures or new properties.

Presently, computational techniques can be applied to a family of materials with a given structure type. Such methods have a reasonable chance of suggesting which materials may possess optimal properties. It may be, however, that one can find the answer more rapidly by combinatorial synthesis methods. Indeed, searching for the specific constituents that optimize a property within a given structural class is the kind of problem ideally suited to that experimental approach.

Yet theorists could potentially contribute to the new materials search in the following circumstances:

- Develop fast "second principles" (e.g. tight binding (Huckel)) or even empirical parameter models to predict trends in a timely manner (preferably available on every experimentalist's workstation).
- More general algorithms to replace those specifically applicable to a limited class of materials, such as only semiconductors or only metals.
- A grand challenge would be to explore structural prediction methods that include atomic diffusion and realistic time scales. For many materials the diffusion rate at the melting point is sufficiently fast that the equilibrium state could be rapidly reached. If such materials have only a few energetic minima in configuration space and they are shallow, then increases in computational speed of 10,000 or so could produce interesting results. Speed increases could come from algorithm development and/or from parallelization and faster compute speed. However, we are not sure what classes of materials will fall into this simple category.

Barriers:

- Almost overwhelming complexity, too many combinations
- Sensitivity of many properties to defects: not easily modeled
- Slowness of computations, need hours not months
- Many practitioners unwilling or unable to undertake challenge, lack of broad knowledge of complex crystal structures and materials trends

In summary, the future of computation in speeding up the materials discovery or optimization process is not as clear as it is for parallel synthesis. However, there are potential areas for development and invention (outside of the expected improvement in computer speed and size — which but themselves alone will not make a qualitative difference in prediction of new materials/properties). How to balance the cost of such potential developments against the cost of relying solely on experimental parallel approaches is unclear. Unless theorists can tackle this challenge, they will become even more marginalized in condensed matter science and technology.

Materials systems that may benefit from a combinatorial approach:
Possible Targets of Interest to DoD

Material	Example	Property to be optimized	Other Probes?
*thermal barrier	ZrO_2 alloys	thermal resistivity	microstructure
* wear resistant coatings	Ti(C,N,..)	hardness, friction	scanning probes

* corrosion resistant coatings	paints	chemical, UV inert	optical readouts
* thermally resistant ceramics	phosphates	low thermal expansion, high thermal conductivity	
* hard magnets at high temp	?	high T_c	dc, ac suscept.
* high T_c.supercond	cuprates??	High T_c	ac suscept, I_c
* actuator matls	PZT:PIN:PT	electrostriction	P, dielectric
* sensor matls	oxides	depends	ionic cond.
* thermoelectrics	REs, semicond	S, rho, thermal cond.	Hall coeff.
* interface materials	?	catalysis, self cleaning	
* NLOs > 5 microns	sulfide ferroelectrics	NLO coeffs.	dielectric const., P
* high dielectric const	oxides	loss tangent	temp. depend.
* low dielectric const	low density	loss tanget	leakage, stability
* thermionic emitters	?	work ftn	conductivity, surface stability

Conclusions and Observations

The opportunity to significantly speed up the materials search and optimization process is at hand. No fundamental scientific barriers are apparent, but considerable development of library synthesis machines, parallel characterization tools and data handling/sharing is needed, especially if the technique is to be widely employed. Much of the development of this approach has taken place outside of academic laboratories – at Symyx and LBL. A few academics may be able to get into the game by modifying existing apparatus or by collaboration with the two groups that are developing these apparatus. However, for significant impact this methodology must be implemented in many places; the libraries studied and data generated needs to be shared to avoid considerable duplication of effort.

The opportunity for computation to contribute to this discovery process appears to be more limited at this time. Yet specific advances in algorithm development and possibly in computer speed, should allow us to further understand the limitations of such approaches and possibly to find classes of materials where computational techniques are well poised to undertake. In fact not much has been done in this area. Indeed theorists have largely shied away from this challenge due to the complexity of the problem. Attracting more of the best and brightest to consider the challenges may prove productive. But the challenges are formidable.

Combinatorial and/or Computationally Guided Synthesis of New Materials

Frank DiSalvo, Henry Ehrenreich and Mac Beasley

Objective

Critically examine the possibility of speeding up (by orders of magnitude) the discovery, optimization and development of new and useful materials.

Relevance to DoD

Many DoD systems are limited by materials performance or by lack of any material to meet a recognized need (e.g. thermoelectric cooling devices). Current methodology is largely a one-at-a-time preparation of modified or new materials. A more efficient process could greatly impact the ability to meet DoD needs in new materials.

Scientific & Technical Summary

Central Questions Considered at Workshop:

- What is state of the art now?
- What are scientific and technical barriers to implementation?
- Can these barriers be overcome in 5 – 10 years? At what level of effort?
- What specific materials/properties should be targeted? DoD relevance?
- Can and how can experiment and theory be used synergistically?

Symyx and LBL developing combinatorial materials synthesis (champion, Peter Schultz). Demonstrated methodology and some initial success: new phosphor systems, etc. Scheme to build 10,000 pixel libraries.

In long term expect combinatorial approach will:

Lead to new synthetic principles (e.g. understanding and controlling complexity in structure and composition of single phase materials).

Make practical multi-step routes to synthesis and to multi-functional materials.

Accelerate discovery of new materials (including metastable phases) and of new or improved behavior.

Other observations include:

For new materials/phenomena, an existence proof is good enough to attract.appropriate interest; negative results do not prove non-existence.

For materials optimization, it is important to be close to real processing conditions and perhaps even sample size, in order to avoid effects of "hidden " variables.

Processing under either kinetic or thermodynamic control should be possible.

Best informatic approach to libraries is not clear — both in library design and data storage/dissemination. Need to minimize relearning.

Characterization:

Need rapid parallel methods, easy display of results.

Techniques:

- Optical (CCD cameras) — emission, ΔT, Faraday rotation, ...
- Electromagnetic: contactless or probes, latter is challenging when # of pixels > 1000
- Mechanical: MEMS (STM, AFM, microindenters,.), little work done here
- Chemical/Structural Characterization — probably serial — interesting pixels only?

Caution: at most compositions the product will be multi-phase. May be a problem or an opportunity.

Computation:

- Currently composition & structure must be known to calculate anything. Cannot predict or calculate (ab initio) stable structures, although empirical rules help to find other members of a known class.

- Presently can calculate trends in a known class of materials as a function of composition (fixed structure). Generally takes too long, weakly coupled to experiments.

Future of Computation:

Develop fast "second principles" (e.g. tight binding (Huckel)) or even empirical parameter models to predict trends in a timely manner.

More general algorithms to replace those specifically applicable to a limited class of materials, such as only semiconductors or only metals.

A grand challenge would be to explore structural prediction methods that include atomic diffusion and realistic time scales. Increases in computational speed of 10,000 or so could produce interesting results. Speed increases could come from algorithm development, from parallelization and/or faster compute speed.

Barriers:

- Almost overwhelming complexity, too many combinations
- Sensitivity of many properties to defects: not easily modeled.
- Slowness of computations, need hours not months.
- Many practitioners unwilling or unable to undertake challenge, lack of broad knowledge of complex crystal structures and materials trends.

Targets of possible interest to DoD:

- Coatings: corrosion or wear resisitant
- Thermal barriers
- Thermally resistant ceramics
- Hard magnetic materials with high T_c
- Actuator materials
- High T_c.superconductors
- NLOs for > 5 microns
- High dielectric constant: passive hf devices
- Low dielectric constant for VLSI etc.
- Thermoelectrics
- Electrochemical and catalytic materials
- Multifunction materials
- Thermionic emitters
- Sensor materials

Conclusions and Observations

- Opportunity to significantly speed up process in materials discovery/optimization is emerging

- Experimentally no basic barriers to implementation, but synthesis and characterization instrumentation needs more development and general availability.

- Data base management and information sharing will become an issue.

- Opportunities for computation are more long term and perhaps more limited: Challenges —

  Develop fast "second principles" models to.predict trends in a timely manner.

  Algorithms for fast computation of total energies

  Grand challenge: structural prediction

IN-SITU SENSORS FOR THIN FILM DEPOSITION

ACCELERATING THE DEVELOPMENT OF COMPLEX THIN FILM TECHNOLOGIES

M. Beasley, H. Wadley, A. Heuer, and R. M. Osgood

EXECUTIVE SUMMARY

Objective

The objectives of this workshop were a) to assess the prospects for measuring in-situ and in real time the temperature, composition and structure of a growing film, and b) to evaluate it as a means of greatly accelerating the development of thin film technologies made from complex thin films. By "complex" we mean materials with multiple components and complicated internal structure.

Relevance to DoD

Superiority of military systems requires exceptional levels of functionality beyond those achievable by potential adversaries. Increasingly this depends on the use of thin film materials with extreme properties — properties that typically require precise composition and microstructural control. DARPA is currently developing many such materials, with an emphasis on those whose functionality hold the prospect of greatly extending system performance.

Table I lists several thin film materials of growing interest to DARPA and DoD. They are manifestly complex. They contain as many as 4 elements. Their atomic structures are correspondingly complex. Most are oxides and subject to the complex chemistry of oxygen that is in no small part responsible for their interesting properties. Even in the more chemically simple examples (e.g., the shape memory alloy TiNi), composition must be maintained to within 0.1% for reasonable performance. The complexity of these materials taxes present thin film deposition processes. Their compositions are difficult to discover, the optimal processes that maximize performance are expensive to develop and the yields are often small driving cost upward. In short, it is not easy to find the "sweet spot". Their complexity is also beyond that for which current or even near term ab initio or film growth theoretical modeling capabilities are likely to be highly reliable, although such models will be of great qualitative value in guiding the experimental process and may help accelerate the development of these complex materials. Their greatest short term impact may be as part of the software used to extract the condition of the film from sensor output data.

TABLE I

Metal multilayers for GMR sensors/MRAM (Co/Cu/Co)
Thermal barrier coatings ($Y_XZr_{1-X}O_2/Al_2O_3$)
High T_C superconductors ($YBa_2Cu_3O_7$)
CMR manganate perovskites ($La_{1-X}[Sr, Ca, Ba]_XMnO_3$)
Photovoltaics ($CuIn_{1-X}Ga_XSe_2$)
Ferroelectrics/ferrites (Ba Sr TiO_3)
Actuator materials ($PbZrTiO_3$, TiNi)
Thermoelectrics (skudderites)
Optical/microwave isolators (YIG)

As materials complexity increases, ways must be found to contain the escalating cost of process development, especially for the limited military market. Hence there is a pressing need for better tools to aid the experimental development of these materials and the deposition processes capable of manufacturing them in useful forms. There is a need for in-situ thin film deposition sensors that can measure accurately and in real time the fundamental variables governing the growth of such complex films. Chief among these is the temperature, composition and structure of the growing film itself, not secondary variables such as the temperature of the substrate and the composition of the source material, as is representative of the present situation. Such tools appear essential in order to greatly accelerate the development of these materials for DoD applications. They may even be essential for success in some cases. Ultimately tools that reveal particular conditions of the materials (e.g. stress, surface morphology, etc.) will also be important.

Results

The speakers at the Workshop were selected to represent new ideas for the in-situ sensing of the temperature, composition or structure of a growing film. They were also chosen to represent various physical probes (e.g. optical radiation, X-rays and electrons) that can be used for such purposes. Each speaker was challenged to address what might be possible in, say, a 5-year time frame. It is clear that there are many good ideas and the speakers were generally optimistic. Some highlights include the following.

A scheme for measuring the absolute temperature of a growing film in real time using Fourier Transform Infrared Spectroscopy — essentially a broadband pyrometer — has been developed by On-Line Sensors. The instrument simultaneously measures the radiance and the optical properties (and hence the emissivity) of the material to extract its blackbody radiation curve, from which absolute temperature can be determined. They report a 1 degree C absolute accuracy. The instrument uses real time computations to extract the temperature from physical measurements. It represents an excellent example of what is possible. At the same time, the optical properties derived as part of the measurement process provide further information about the nature of the film that can be used for materials and process optimization.

The use of Raman optical spectroscopy to determine the absolute temperature of a growing film independent of specific material properties also shows promise. It will be most useful for nonmetallic material for which strong Raman lines can be expected.

A practical scheme for measuring the composition of a growing film based on X-ray Photoelectron Spectroscopy (XPS) was proposed by a group from Stanford. Based on existing components configured specially for in-situ use, the system appears capable of measuring composition in-situ to 5% with a 0.1 second averaging time and to 0.1% with a 10 second averaging time. The approach is extremely surface sensitive — an essential requirement for precise composition control during deposition for materials where stoichiometry is critical. The associated real time computational needs have not been addressed.

With some approaches it is possible to sense both structure and composition. A well-known qualitative probe of the structure of a growing film is Reflection High Energy Electron Diffraction (RHEED). By simultaneously carrying out Electron Energy Loss Spectroscopy (EELS) on the electron beam, chemical composition information can be extracted. In the context of RHEED this is known as REELS. The use of parallel data extraction using a CCD detector array permits real time operation. Like XPS this approach is very surface sensitive. This instrument has been developed at Cal Tech and is being commercialized by Thermionics, Inc. The use of computation to extract quantitative structural information and to speed up composition determinations have not yet been fully exploited. This is a nontrivial undertaking in the case of RHEED, as it is subject to the problem of multiple electron scattering.

Another approach capable of simultaneous extraction of structural and chemical information is X-ray Diffraction/Fluoresence. This approach is being explored in the Hitachi Central Research Lab. It probes deeper than XPS and RHEED/REELS. The innovation here is the use of a capillary light pipe to channel the X-rays into the deposition system and to focus them onto the growing film. The technology of such X-ray light pipes and their associated X-ray generation sources are undergoing rapid development and the approach shows great promise. The computational needs to make this a real time system do not appear to have been addressed.

On the other hand, building on work done earlier at Arizona State University, Motorola has been using low angle X-ray scattering to determine the layer thicknesses and interface roughness of GMR magnetic multilayers. The approach is based on sophisticated modeling of the scattering data. In particular, a surface morphology model is used in a nonlinear analysis of the scattering data to deduce RMS surface roughness.

Findings

- There are many very creative ideas around on how to do *in-situ* sensing of the temperature, composition and structure of growing films. There is growing reason for optimism that such sensing can be done with useful precision. It is harder to assess to what degree all of these approaches could be done in real time, but estimates are favorable and the use of modern electronic technologies and high speed digital signal processing have hardly been exploited in most cases.

- On the other hand, this work is being done largely as a "cottage" industry by "green thumb" experimentalists. It is not being done in larger organizations (or groups) capable of integrating the physical sensors with the needed modeling and associated software for fast data extraction.
- It is uniformly recognized that in the long run, it will be essential to extend these techniques to deal with the inhomogeneities (desired or undesired, vertical and lateral) in real films. While the participants were not selected for their expertise in modeling, it is clear that this is potentially a difficult "inverse" problem, in which the nature of the input probe and the output signal are known and the state of the material is to be determined.

Conclusions

- Prospects appear good for real-time *in-situ* sensing of primary variables (temperature, composition and structure) of a growing thin film.
- They will require stimulus, however, to focus attention on the need/opportunity and increased use of modeling.
- Success will greatly accelerate availability (and reduce development costs) of complex thin film of extreme functionality for DoD needs. It may even be essential for some materials.
- They will play a critical role in validating atomistic models of real thin film growth (e.g., in the DARPA VIP program) that eventually can be used to design even more powerful thin film deposition control systems.

In-situ Sensors for Thin Film Deposition

(Accelerating the Development of Complex Thin Film Technologies)

M. Beasley

H. Wadley

A. Heuer

R. Osgood

Objective

- To asses the prospects of measuring in-situ and in real time the temperature, composition and structure of a growing film.
- To evaluate it as a means of greatly accelerating the development of thin film technologies made from complex thin films.

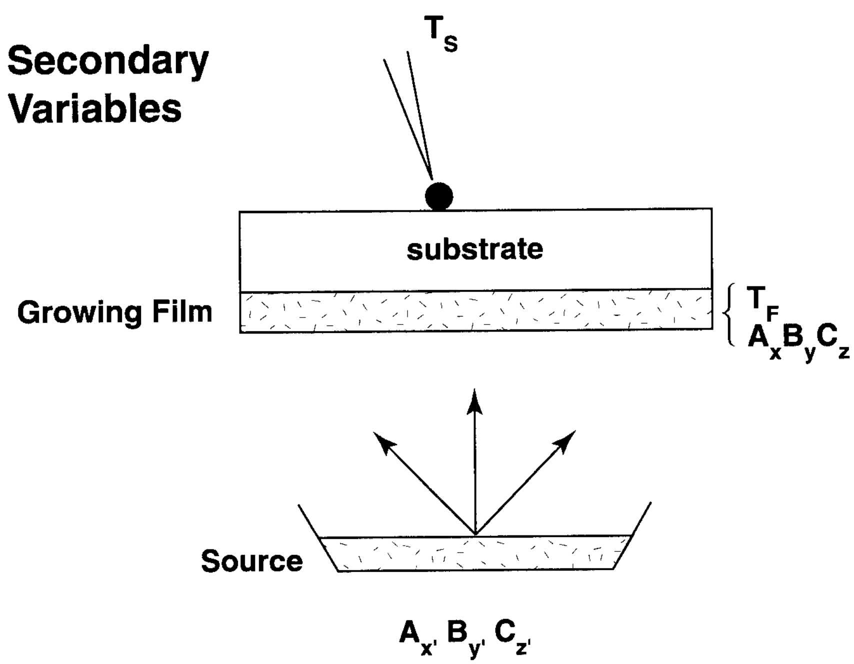
DOD Relevance

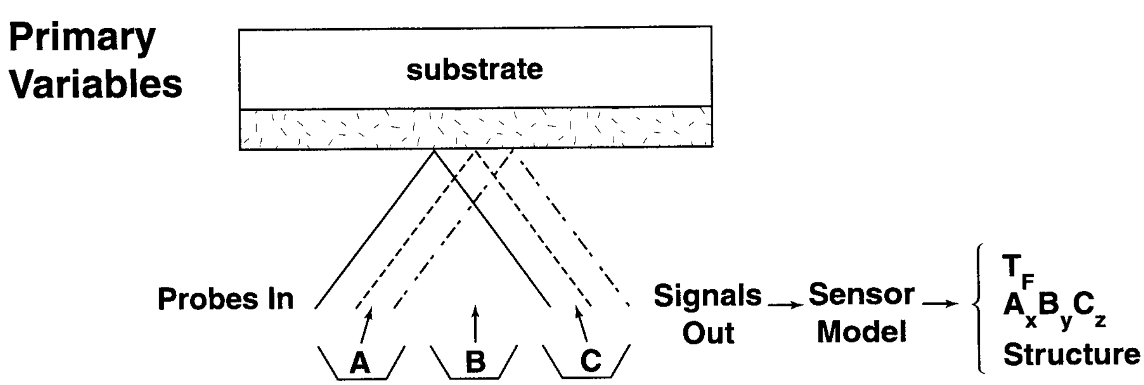
The highly functional materials of interest to DoD come at a price. They are complex, multicomponent materials that require new approaches to thin film deposition process control.

- Metal multilayers for GMR sensors/MRAM (Co/Cu/Co)
- Thermal barrier coatings ($Y_xZr_{1-x}O_2/Al_2O_3$)
- High Tc superconductors ($YBa_2Cu_3O_7$)
- CMR manganate perovskites ($La_{1-x}[Sr, Ca, Ba]_xMnO_3$)
- Photovoltaics ($CuIn_{1-x}Ga_xSe_2$)
- Ferroelectrics / ferrites (Ba Sr TiO_3)/(YIG)
- Actuator materials ($PbZrTiO_3$, TiNi)
- Thermoelectrics (skudderites)

How To Do Better

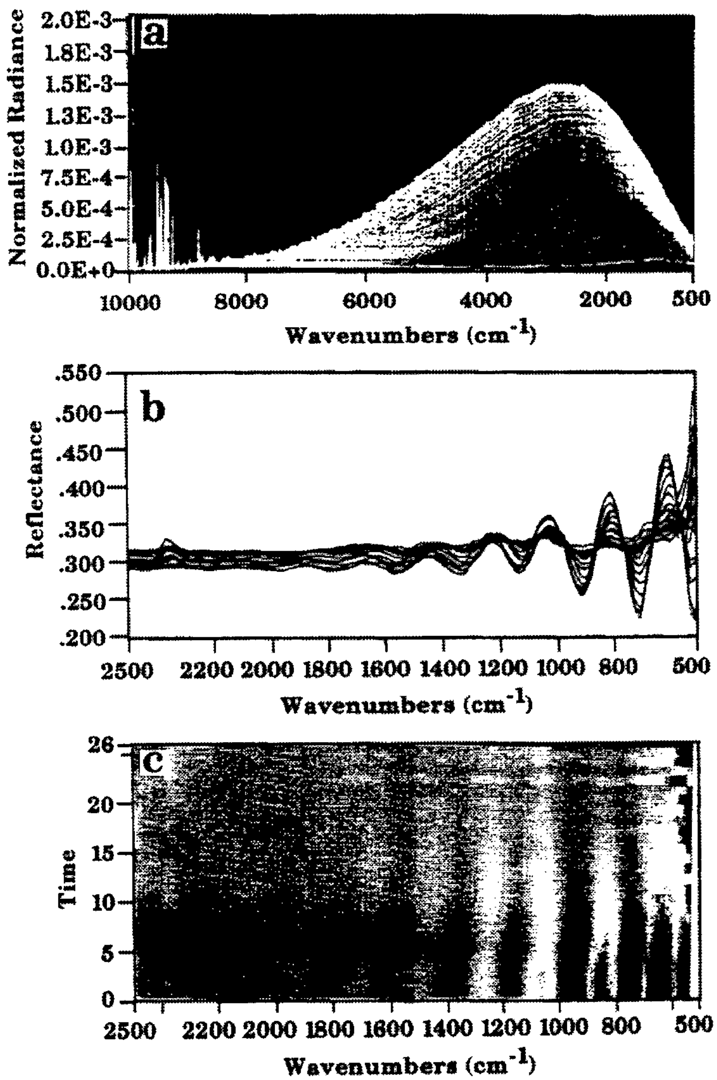
Sense Primary Growth Variables





Absolute Temperature from Fourier Transform Infrared Spectroscopy

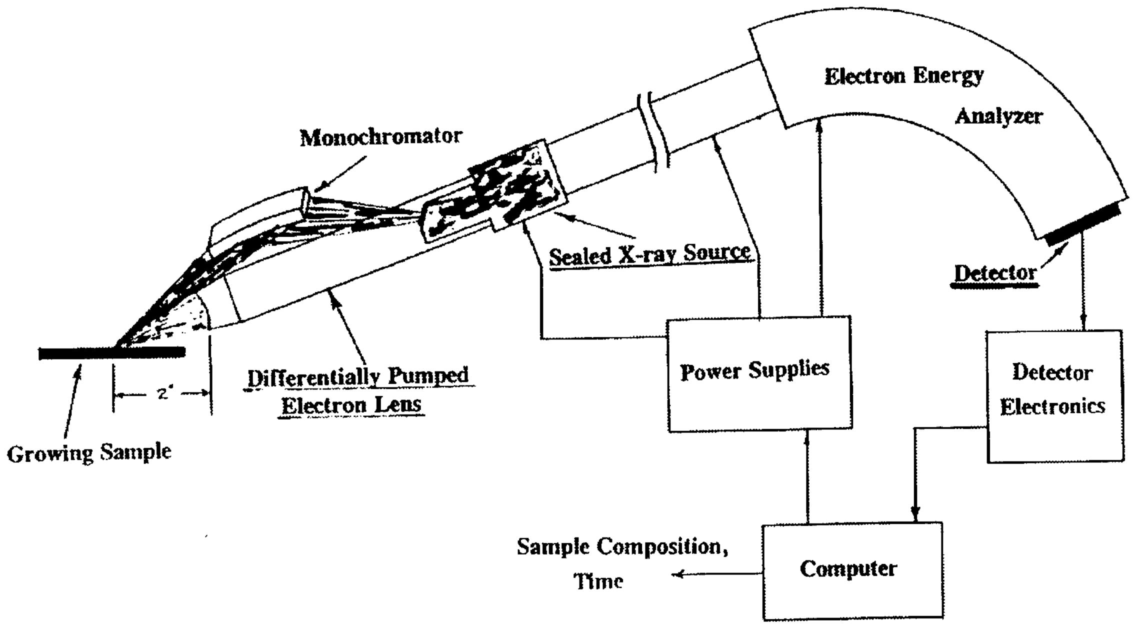
(Broad Band Pyrometry)



ON-LINE TECHNOLOGIES INC.

Process and Environmental FT-IR Monitors

Composition Determination by X-ray Photospectroscopy (XPS)

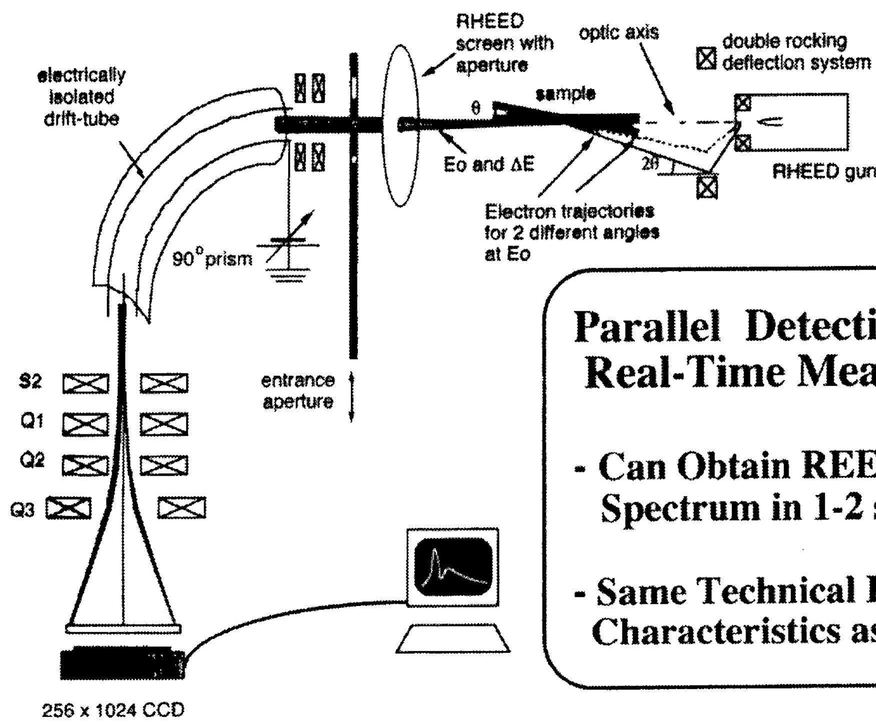


<u>Projected Performance:</u>

Sampling Time	10 msec	10 sec
Composition Precision	5%	0.1%
Surface Sensitivity	0.5 monolayers	
Working Distance	2 inches	

Stanford

Structure/Composition from RHEED/REELS



Parallel Detection Enables Real-Time Measurements:

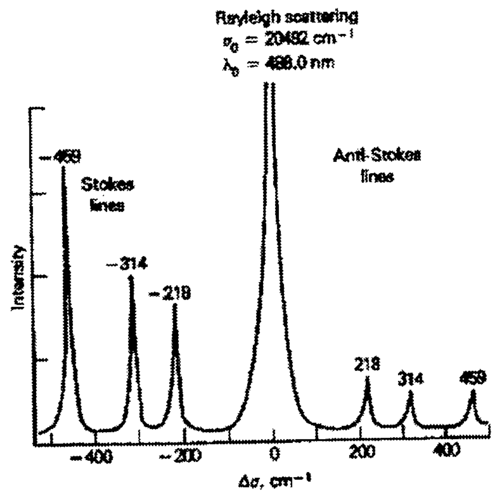
- Can Obtain REELS Spectrum in 1-2 seconds
- Same Technical Performance Characteristics as Serial System

CalTech/Thermionics

Absolute Temperature from Raman Optical Spectroscopy

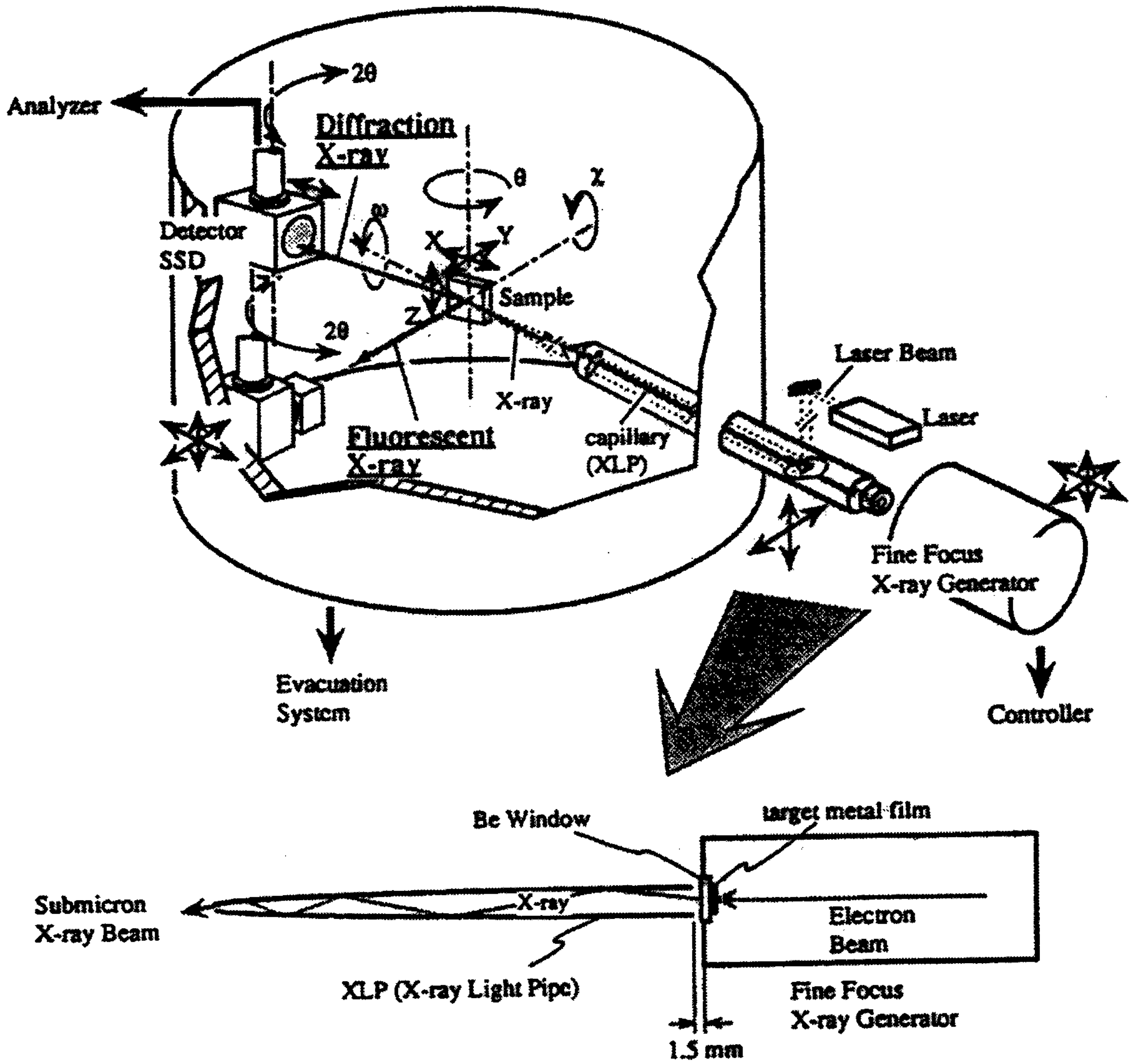
- Ratio of Stokes/AntiStokes given by Boltzman Factor

$$\frac{I_{Stokes}}{I_{Anti\ Stokes}} = \mathrm{Exp}\left(-\frac{\mathrm{Raman}}{k_B T} \right)$$



Structure/Composition from X-ray Diffraction/Fluoresence

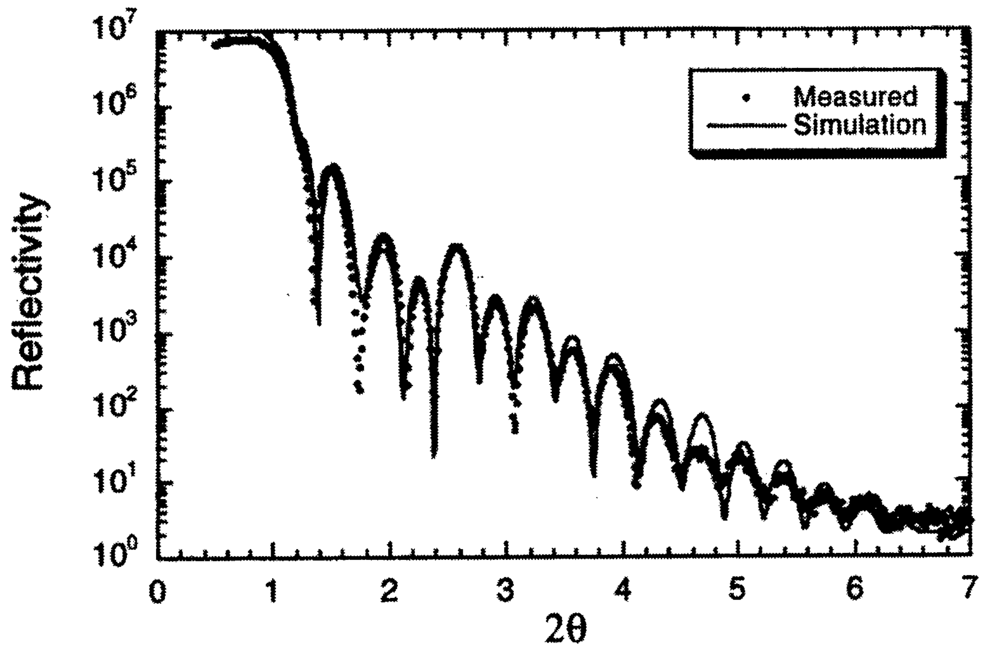
(X-ray Light Pipes)



Central Research Lab – Hitachi

Structure/Roughness from X-ray Scattering

Measures layer thicknesses and interface roughness in ultra-thin layered films.



Structure: NiFe: 23 Å – Co: 14 Å – Cu: 30.6 Å – Co: 14 Å – NiFe: 63 Å – Ta: 101 Å – TaO_2 27 Å

Motorola/Arizona State University

Findings

- There are many creative ideas out there.
- Being done as a “cottage” industry, however.
- Modeling of the sensing process is still primitive for the most part.
- Modeling for inhomogeneous films is difficult but particularly important.

Conclusions

- Prospects appear good for real-time in-situ sensing of primary variables (temperature, composition, and structure) of a growing thin film.
- Will require stimulus, however, to focus attention on the need/opportunity and increased use of modeling.
- Success will greatly accelerate availability (and reduce development costs) of complex thin film of extreme functionality for DoD needs. It may even be essential in some cases.
- Will play a critical role in validating atomistic models of real thin film growth (e.g., in the DARPA VIP program) that eventually can be used to design even better processes.

DARPA/DSRC MILITARY VISITS
(Exercises, Wargames and Concept Demonstration)

R. C. Lytikainen

EXECUTIVE SUMMARY

Objective

The DSRC directly supports DARPA's primary mission of sponsoring research and development (R&D) activities to seek, test and apply the newest advances in science and technology for the military user. As the DoD and its military operational forces continue to downsize, the modern warfighter faces increased challenges to sustain what he has, and is looking where he can for anything that can serve as a "force multiplier" to ensure mission success. Given expanded and non-traditional missions such as peace-keeping, pacification, urban warfare, counter-terrorism, and counter-drug operations, complicates his problem, and the warfighter is looking more and more towards technology for near-term help. For a "silver bullet".

Technology may or may not be able to help the warfighter in the near-term. Understanding where technology might help, and where it might not is fundamental to pursuing a good technical solution. And understanding the warfighter's problems is fundamental to that.

The DARPA/DSRC Military Visit and Exercise activitiy provides us with better focus upon the ultimate end users problems. The exposure of leading edge technologists, scientists and engineers to the way the military does business at the unit and individual operations level via participation in and up-close observation of exercises, military unit visits and wargames, continues as an excellent venue for DARPA program managers and DSRC scientists.

Relevance to DoD

All military exercise and unit visits are DoD relevant by definition. DARPA works directly with the military user on field concept demonstration projects, and many of our military/exercise familiarization visits are done in conjunction with these activities.

DARPA-related prototype development and concept demonstration projects conducted or planned during the past year include; Low-power Wireless Integrated Microsensors (LWIM), batteries and fuel cells (High Performance Power Sources), neuron-based biosensors (Biological Weapons Defense/BWD), microinstrumentation cluster for environmental monitoring and automated weather station firing solution (MEMS), broad-band compressive receiver (HTSC), SINCGARS radio and HMMVEE charger (Flexible Photovoltaics), Pathfinder and VUMAN (Smart Modules, Warfighter Visualization), mobile radio propagation improvement (HTSC/Cryo Cooler), infrared illuminator (Low Light-level IR), low-cost ground instrumentation (Electronic Packaging/Distributed Sensor Systems), mine detection (UXO/Land), optoelectronics (OMNET, FSOIA), two-dimensional acoustical transducer arrays (Sonoelectronics), small unit operations (SUO), low power, silicon RF communications (Composite CAD), MMIC battelfield ID (MAEFET), compressed digital photography (APS Camera) and electronic warfare (A/D Convertor/Digital Receivers). The DSRC also conducted a "Uninhabited Vehicles Study" during the year, reported on page 23 of this report.

Activities

Military visits are scheduled both "off conference" and "on conference". Virtually every active member of the DSRC participated in at least one of these visits during the past year (i.e., since the 1996 DSRC Summer Conference). DARPA program managers often request slots for their contract agents, as well as their contractors. For DARPA, participants in these visits have been almost exclusively DSO and ETO. Recently, other DARPA technologists have been invited on a "slot available" basis.

The numbers include; 24 DSRC, 39 DARPA (15-DSO, 14-ETO and 10 from TTO, ISO, ITO and DIRO), 44 Army, Navy/Marine Corps, and Office of Naval Research (ONR) agents, Army Materials Command Field Assistance in Science and Technology (AMC/FAST) and Naval Science Assistance Program (NSAP) Science Advisors and 13 DARPA contractors, for a total of 120 military activity-person visits. Since the inception of this program in March 1992, a total of 747 person-visits have been conducted to 73 commands, ships and operational units of all the armed services.

Off-Conference

"Off conference" visits are usually set up in conjunction with the Navy/Marine Corps NSAP, the Navy's "Scientist-to-Sea", and the Army's AMC/FAST program. Air Force visits are set up directly with operational commands, since they have no "field" science advisor program.

DSRC scientists and DARPA program managers participated in 24 off-conference military exercises, military installation visits and wargames since the 1996 DSRC Summer Conference. These visits are summarized below.

On-Conference

"On-conference" visits are coordinated with the DSRC Summer Conference Studies and Workshops to reflect both the shifting priorities within DOD and DARPA and/or to supplement the discussions at hand. With interest centered around several areas including; counterterrorism, smart bullets/weapons, uninhabited/autonomous vehicles, joint military operations, improving human performance, and small unit operations, the following four activities were conducted:

CENTCOM — Mr. Earl Rubright, Science and Technology Advisor to United States Central Command (CENTCOM) visited the DSRC, briefed an overview of the CENTCOM Area of Responsibility (AOR), and led a provacative discussion on technology challenges and issues in the context of the "real world", focusing on the individual soldier, small units, small devices and small cost.

COMTHIRDFLT — VADM Herb Browne, Commander, Third Fleet, hosted an at-sea visit aboard the USS Coronado by DSRC/DARPA scientists during a major Joint Task Force Exercise (JTFEX) being conducted in the Eastern Pacific.

CGIMEF — Mr. Chuck Francis, NSAP Advisor to Commander, First Marine Expeditionary Force, hosted a visit to "Red Beach" at Camp Pendleton by DSRC/DARPA scientists to observe the amphibious assault phase of the JTFEX discussed above.

NCCOSC/NRAD — Mr. Jeff Haun, Director, Navy Fleet Mammal Division, hosted a visit by DSRC/DARPA scientists to observe MK4, MK6, and MK7 System Training/Demonstration, and briefed the increasing augmentation of Atlantic bottle-nosed dolphins in naval operations and fleet exercises.

Military Visit Summary

The following 28 visits are partitioned into the categories; Military Exercises/Wargames, Military Installation Visits, Concept Demonstrations/Experiments/PI Meetings and Military/DSRC Workshops/Meetings. Each contains sponsor/host command, location, specific activity conducted, and date (in chronological order). Some DSRC and DARPA personnel participated in more than one of the activities:

- **Military Exercises/Wargames**
  - Chief of Naval Operations (CNO)/Naval War College (NWC)
    Newport, RI
    (Medical Technology Initiative Game "VANGUARD" Wargame) (Aug 96)
  - Chief of Naval Operations (CNO)/Naval War College (NWC)
    Defense Logistics Agency (DLA)
    Fort Belvoir, VA
    (Technology Initiative Game "TIG-96" Wargame) (Sep 96)
  - Marine Corps Air Ground Combat Center (MCAGCC) (4 visits)
    29 Palms, CA
    (Desert Fire Exercise/DESFIREX & LWIM, Flex PV Concept Demos) (Sep 96)
    (STEEL KNIGHT Esercise & LWIM, Micro Instrument Cluster Concept Demos) (Dec 96)
    (Hunter Warrior Exercise/Advanced Warfighting Experiment/AWE) (Mar 97)
    (DESERT SCIMITAR Exercise & LWIM Concept Demo) (Apr 97)
  - Navy Aircraft Carrier at-sea
    USS Constellation (CV64)
    At-sea-Southern Calif Operations Area (SOCAL OPAREA)
    (Flight Operations, Persian Gulf pre-deployment Exercise) (Jan 97)
  - Navy Aegis Destroyer at-sea
    USS Stethem (DDG63)
    At-sea-Southern Calif Operations Area (SOCAL OPAREA)
    (DESRON 21, Persian Gulf pre-deployment Exercise) (Mar 97)
  - U.S. Army National Training Center (NTC)
    Fort Irwin, CA
    (Opposing Force/OPFOR Exercise, Force 21 Experiment) (Jun 97)
  - Commander, Third Fleet (COMTHIRDFLT)
    USS Coronado (AGF11)
    At-sea-Southern Calif Operations Area (SOCAL OPAREA)
    (Joint Task Force Exercise/JTFEX) (Jul 97)

- Marine Corps Base
  Camp Pendleton, CA ("Red Beach")
  (CGIMEF-Joint Task Force Exercise/JTFEX, Amphibious Assault) (Jul 97)

- **Military Installation Visits**
  - Marine Corps Base
    Quantico, VA
    (CommandantUs War Fighting Lab (CWL)-Hunter Warrior/AWE) (Feb 97)
  - U.S. Air Force Base
    Nellis AFB, NV
    (Air Strike Warfare Center, GREEN FLAG) (Mar 97)
  - U.S. Army Base
    Fort Jackson, SC
    (Basic Training Center) (Mar 97)
  - Navy Fleet Mammal Division
    NCCOSC/NRAD, Point Loma,CA
    (MK4, MK6, MK7 System Training/Demonstrations) (Jul 97)

- **Concept Demonstrations/Experiments/PI Meetings**
  - Baraga County Fair
    Pelkie, MI
    (DSRC/DARPA Military Exercise Training Camp-Manure Pitching) (Aug 96)
  - MEMS PI & DoD-Wide MEMS Meetings (2 meetings) (Sep 96)
    Cleveland & Dayton, Oh
  - Marine Corps Base
    Camp Pendleton, CA
    (1MARDIV, IMEF-LWIM, Flex PV (ETO/DSO) ConceptDemos) (Sep 96)
  - U.S. Naval Postgraduate School (USNPGS)
    Monterey, CA
    ("Technology & The Mine Problem" Symposium) (Nov 96)
  - MEMS PI Meeting & Expo
    Berkley, CA
    (California Highway "Path Program" Instrumented Test Vehicle Demo) (Feb 97)
  - GOMAC, Low Power PI Meeting (Mar 97)
    Las Vegas, NV
  - Marine Corps Base
    Quantico, VA
    (CWL-Urban Warrior/DARPA (ETO, ITO) Concept Demos) (Apr 97)
  - Marine Corps Chemical Biological Incident Response Force (CBIRF)
    Henderson Hall

Arlington, VA
(CBIRF Exercise & DARPA/DSO Medical COC Demo) (Apr 97)

- U.S. Army Artillery Training Center
  Fort Sill, OK
  (MET Concept Demo-Army and Marine Corps Artillery) (May 97)

- Dog Sniffing (Artificial Dog's Nose) PI Meeting
  Napa, CA
  (Dog landmine detecting and Marine Corps detecting/defusing demonstration) (Jun 97)

- **Military/DSRC Workshops/Meetings**

  - DSRC Uninhabited Vehicle (UV) Study
    UAV Tour
    Mojave, Palmdale & San Diego, CA
    (Scaled Composites, Lockheed Martin Skunk Works, Teledyne
    Ryan Aeronautical) (Jul 97)

  - United States Central Command (CENTCOM)
    At DSRC Summer Conference, Torrey Pines Elementary School
    LaJolla, CA
    (CENTCOM AOR, Technology Challenges) (Jul 97)

An Ever Changing DSRC/DARPA Lineup

There are several new members and several DSRC members who retired from the council in 1997. A similar story for new DARPA program managers, and some who have left for another position. Those who participate in military visits are presented mementos in the form of a collage of their "DARPA, DSRC and Military Exercise/Wargaming" activities. DSRC retirees were; John Hirth, Evelyn Hu, Tom Kailath, Bob Rapp, and Amnon Yariv. DARPA program managers to whom mementos were presented this year are Randy Harr and Zach Lemnios. Also presented collages in previous years, but not recorded in a previous DSRC Conference Report were; Ben Wilcox (1996), Bill Barker (1996), and Sven Roosild (1995). These collages are all shown in the pages that follow.

Snapshots of "technologists in the field" have turned out to be an important part of the visits-perhaps for a vugraph, or perhaps for no other good reason than to show that "I was there!"

Conclusions & Observations

DARPA and DSRC technologists were exposed to a wide range of military/techno/politico activities in 1996–97, from individual soldier and small unit operations, to those at the top of the joint, operational warfighting chain-of-command. We have seen the Army, Navy and the Marine Corps conducting major experiments in bringing technology NOW! to the battlefield/battlespace with Force 21, JTFEX and Hunter Warrior. And we have been exposed to the rather imprecise, inexacting and highly political Quadrenniel Review (QDR) process at the top of the Armed Services.

The fact that today there are fewer top decision makers in DoD with any military experience than any time since before World War II, may not be important by itself. What is important is that he who makes these decisions, and he who researches, develops and acquires systems for the military listen carefully to the warfighter. There is absolutely no substitute for walking in the shoes of the warfighter and learning that mud, dust, salt water, heat, cold, humidity, lack of sleep, getting beat-up-bouncing-across-the-terrain-in-an-AAV, and MREs are all part of the hi-tech system being delivered to that Marine Lance Corporal that you spent a couple days with at 29 Palms last month.

MILITARY EXERCISES

R. C. Lytikainen

31 Jul 97

DARPA/DSRC Military Visits

(Purpose)

- Build Intuition via Exercises, Wargames, and First-hand Observation (10)
- Early Concept Demo of Potential Military Application and Technology Insertion (7)
- DARPA Principal Investigator (PI)-Related (7)

Links via Military Science Advisors
- Navy/Marines (NSAP, Scientist-to-Sea)
- Army (AMC/FAST)
- Air Force (TECH CONNECT, Direct)
- U&S Command S&T Advisors

31 Jul 97

DARPA/DSRC Military Visits

(Participants)

- DSRC - 30 or so "world-class" scientists, mostly academia, 30th year supporting DARPA/ARPA
- DARPA - 40 or so DSO/ETO program managers
- Other - 25 Navy/Air Force/Army Agents + Contractors

- Numbers - 747 person-visits, 73 Commands/Ships/ Operational Units - March 1992 to today
- Since 1996 Summer Conf:
  - 39 DARPA (15-DSO, 14-ETO, 10-TTO/ISO/ITO)
  - 24 DSRC
  - 44 Army, AF,Navy, Marine Corps Agents/SciAds
  - 13 Contractors

  120

Military Visits

(Bottom Line)

LESSONS LEARNED (and some intuition built):

- 3rd World, Terrorist Weaponery
- Indigenous Forces Seldom Lose
- Dog Sniffing Beats Technology
- The Buffaloes Still Roam
- CBIRF Will Probably Be Needed In Today's World
- Some Marines Believe Their AAVs Can Fly
- MREs Are A Little Known Delicacy
- The Spoils Of Victory Are Sweet
- 19" Racks Are Not Only For Electronics

31 Jul 97

Military Visits

(Bottom Line)(Cont.)

LESSONS LEARNED (and some intuition built):

Responsibility Of Command At Sea

Harvesting Energy From Environment-Good PR

Strapping On Mae West, Tail Hookers

Concertina Wire Can Ruin Your Day (and night)

“Hurry Up And Wait”

Desert Warfare-Dust, Dust And More Dust

Marines Willing To Try Anything-Even Technology

Wireless AAV Comms New Start-Randy Harr

DSRC/DARPA Should Stick To Technology

1997DSRC SUMMER CONFERENCE

DSRC Retirees (Hirth, Hu, Kailaith, Rapp, Yariv)

CENTCOM AOR, Tech Challenges (Earl Rubright)

Full Moon-No Grunions!

At-Sea With COMTHIRDFLT-JTFEX (VADM Browne)

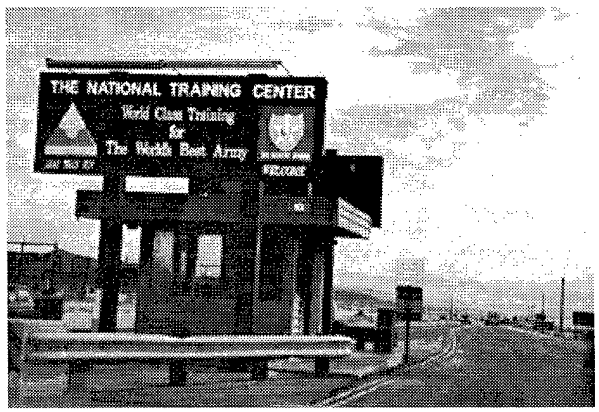
Assault On Red Beach (LGEN Fulford/Chuck Francis)

Fleet Mammals On Ascendancy (Jeff Haun)

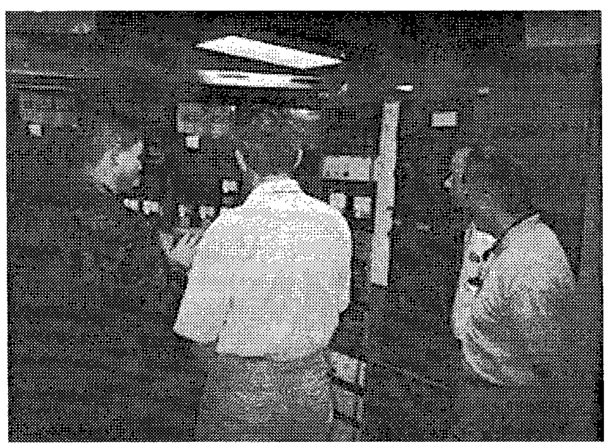
DSRC/DARPA Summer Training Camp-Manure Pitching

U.S. ARMY NATIONAL TRAINING CENTER (NTC), FT. IRWIN, CA (JUN 97)

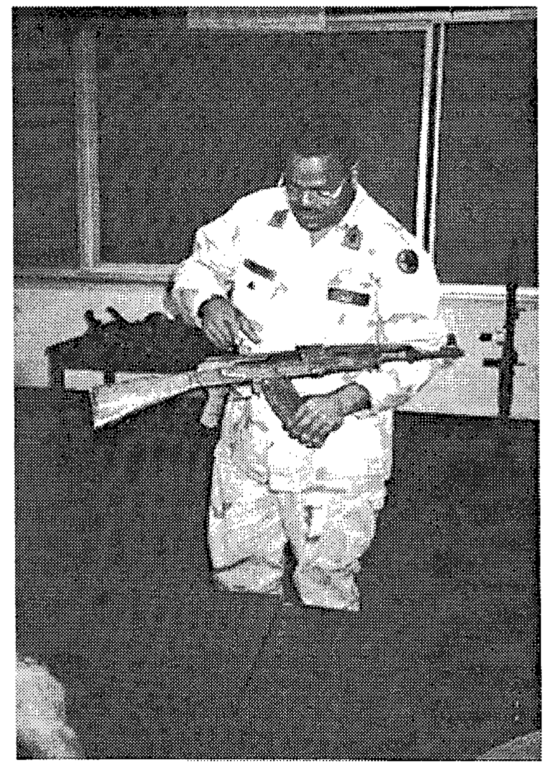
(DARPA–Pease, Frink, Garvey, Headley, Krug, DSRC–Bowers, Wadley, Lytikainen, AMC/FAST–Heilman)(OPFOR VS BLUEFOR - 2ID + ARNG)



NTC



"Star Wars" Battlefield Instrumentation Facility



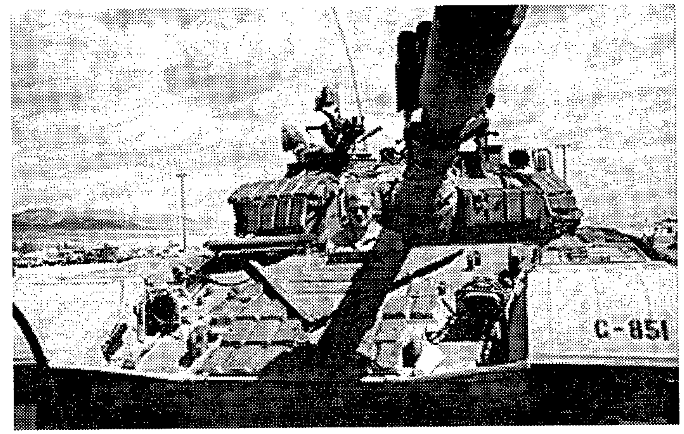
AK-47 Training

808-6-27-97-15

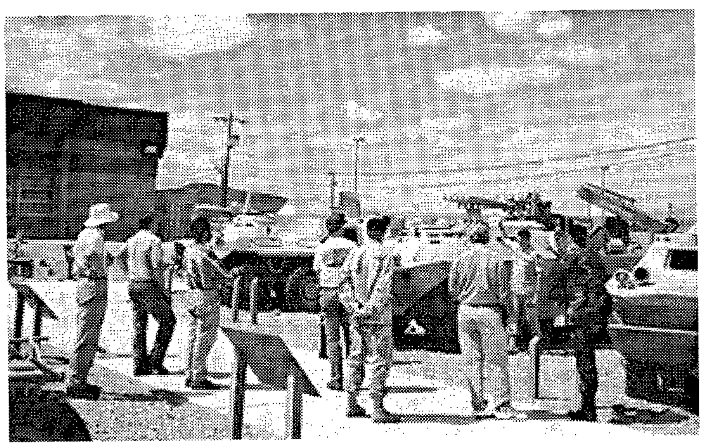
U.S. ARMY NATIONAL TRAINING CENTER (NTC), FT. IRWIN, CA (JUN 97)

(DARPA–Pease, Frink, Garvey, Headley, Krug, DSRC–Bowers, Wadley, Lytikainen, AMC/FAST–Heilman)(OPFOR VS BLUEFOR - 2ID + ARNG)

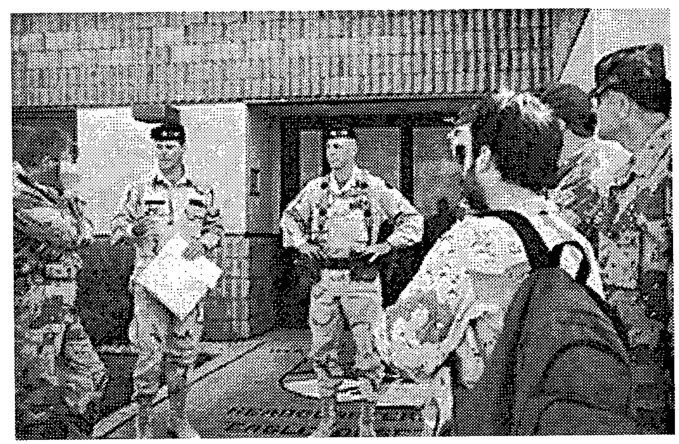
Motorcycle Gang



Haydn “Dukakis” Wadley



Captured Soviet Equipment



OPFOR XO Pre-Exercise Brief

808-6-27-97-16

UXO/LANDMINE – DOG SNIFFING PI KICKOFF NAPA, CA (JUN 97)

(DARPA–Dugan, Urban, Tsao, DSRC – Lytikainen, Agents – Army, Navy, Air Force, NSAP – Kiers)

Col Barrett, SAA (Ret.) Explains Field Demo

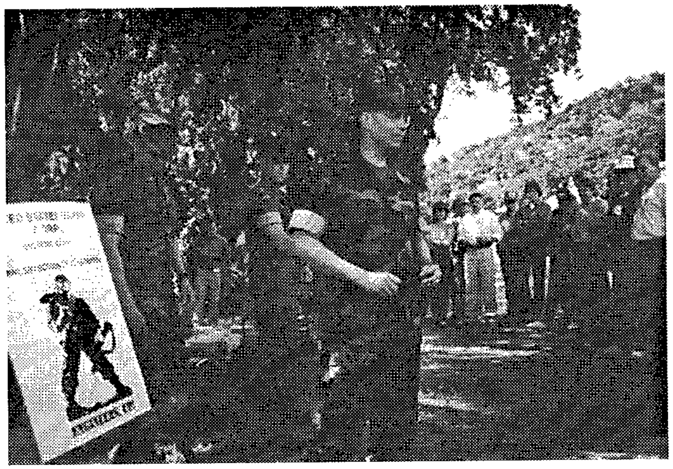
"Tara" In Search Mode

"Tara" Finds Land Mine

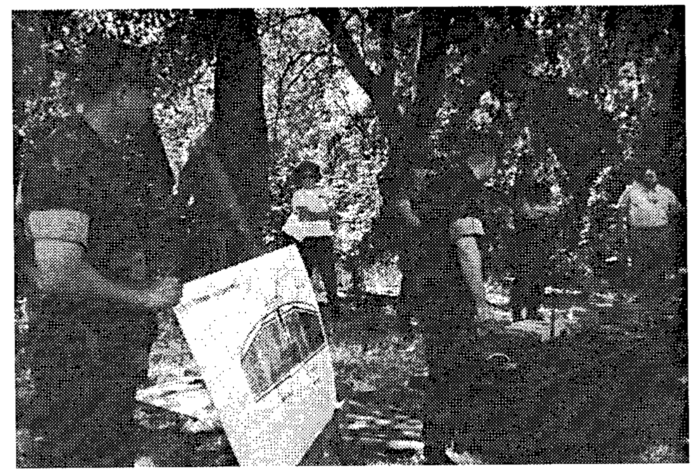
808-6-27-97-20

UXO/LANDMINE – DOG SNIFFING PI KICKOFF NAPA, CA (JUN 97)

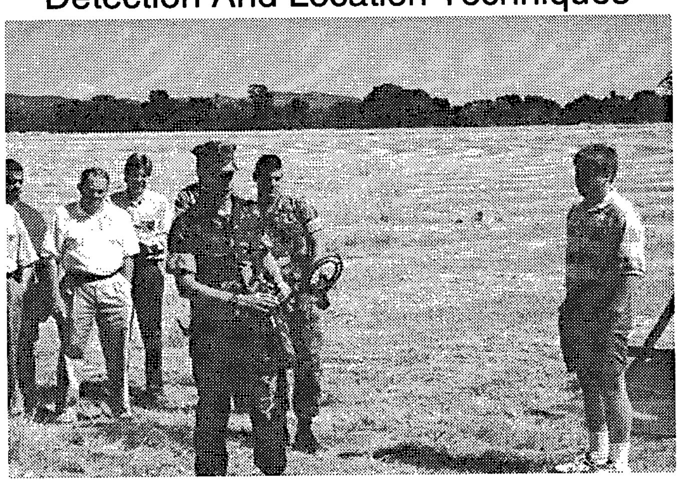
(DARPA–Dugan, Urban, Tsao, DSRC – Lytikainen, Agents – Army, Navy, Air Force, NSAP – Kiers)



GYSGT "Gunny" Crane – Current Mine Detection And Location Techniques



Land Mine Display



SGT Christian Demonstration

PIs Try Their Hand At It

808-6-27-97-21

U.S. ARMY FIELD ARTILLERY TRAINING, FT. SILL, OK (MAY 97)

(AMC/FAST–Reynolds, NSAP–Kiers, DSRC–Lytikainen)

"Oh Give Me A Home..."

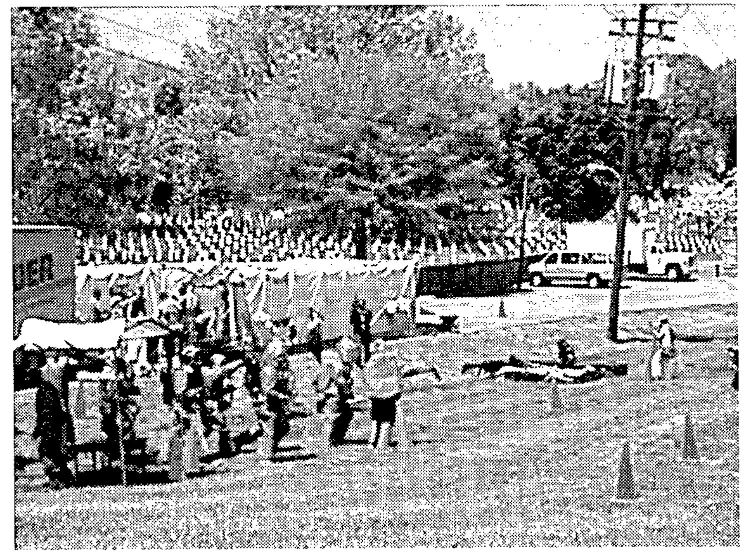
808-6-27-997-8

U.S. MARINE CORPS CBIRF EXERCISE

HENDERSON HALL MARINE CORPS ANNEX – ARLINGTON, VA APR 97

(DARPA - ALEXANDER, DUBOIS, MORSE, SILVA, DSRC - LYTIKAINEN)

GERMAN-MADE XM-93
FOX RECON VEHICLE



LEVEL-3
CHEM/BIO SUITS

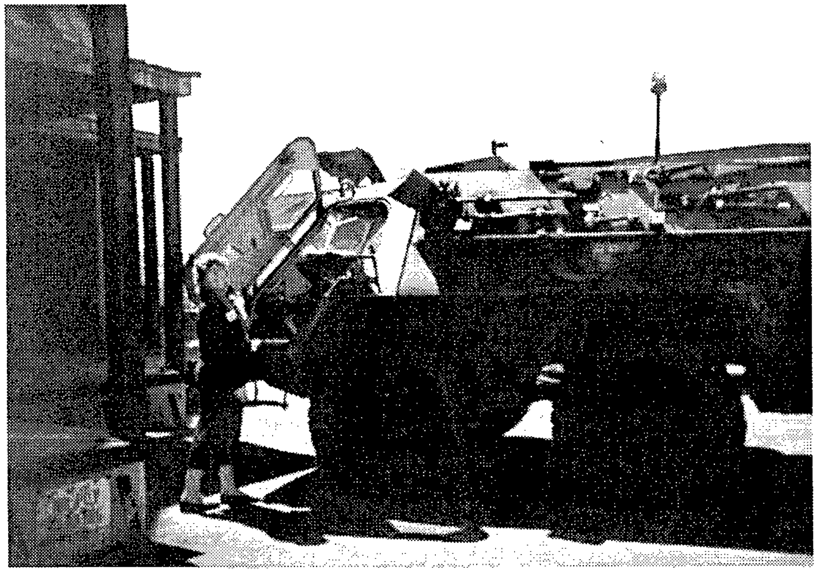
CASUALTIES LEAVING
THE SCENE

WASHING DOWN AT
DECON STATION

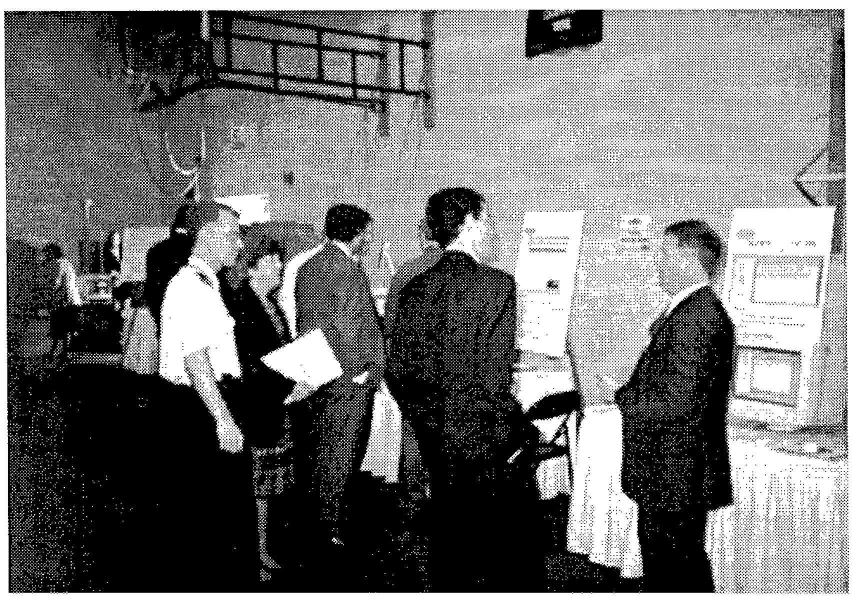
U.S. MARINE CORPS CBIRF EXERCISE

HENDERSON HALL MARINE CORPS ANNEX – ARLINGTON, VA APR 97

(DARPA - ALEXANDER, DUBOIS, MORSE, SILVA, DSRC - LYTIKAINEN)



XAN AND THE FOX

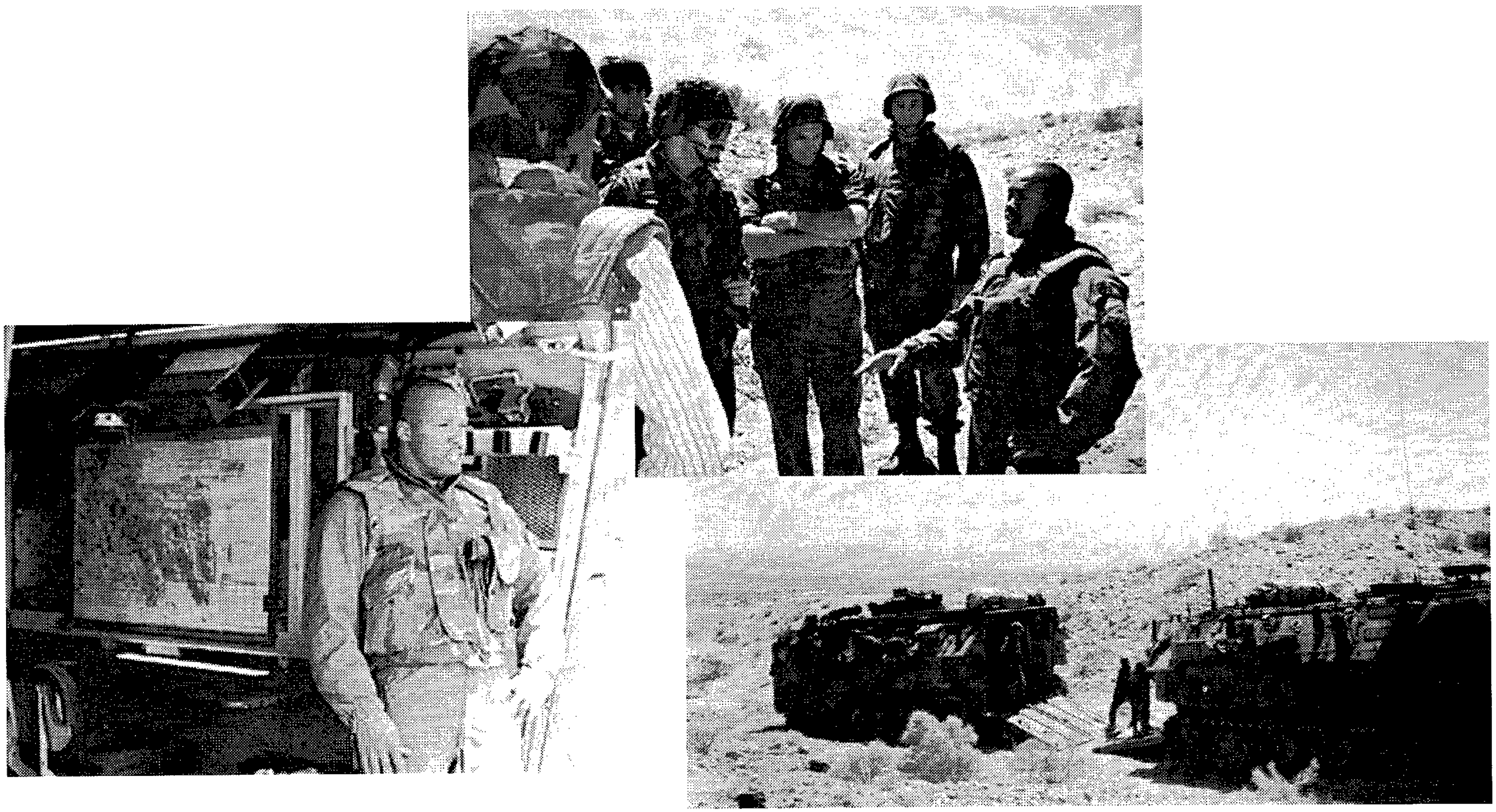


SILVA, BWD ADVANCED INFOMATICS

MORSE IN THE FOX

MCAGCC, 29 PALMS, CA (SCIMITAR – APR 97)

(Husain, Leheny, Mrksich, Wadley, Lytikainen, AMC/FAST (2), NSAP, UCLA/RSC (4) (1 Mar Div)

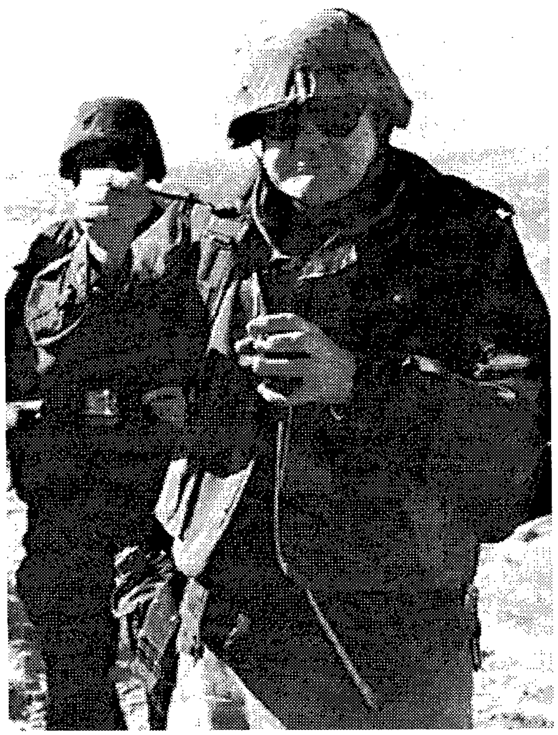


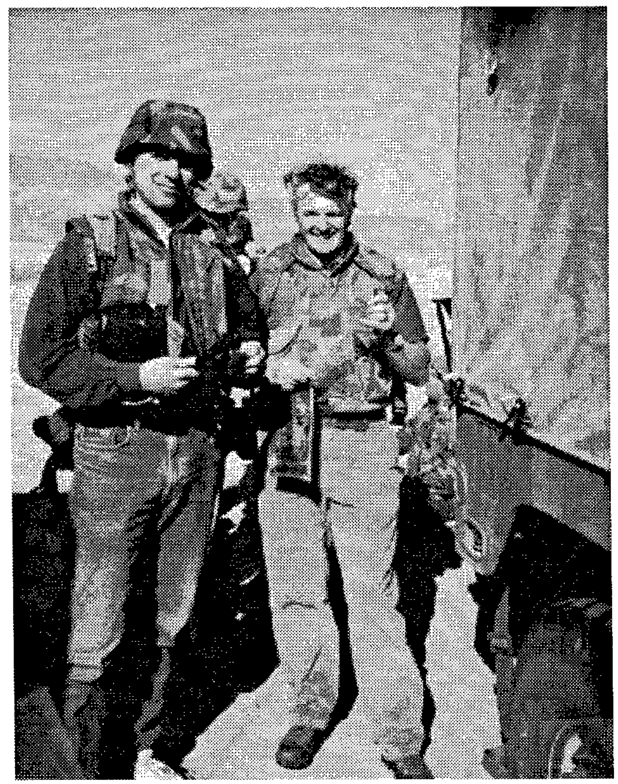
SSG Jackson And His AAVs – “Marines Love This Vehicle....Some Believe They Can Fly.”

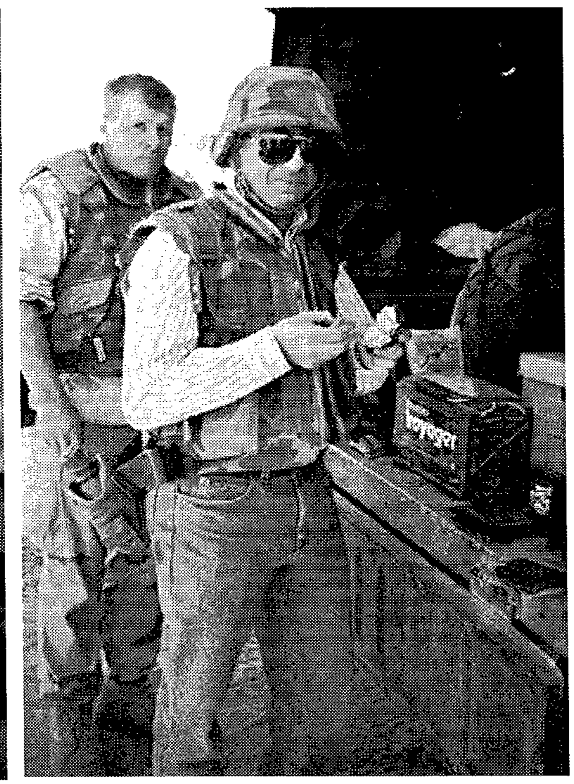
808-6-27-97-5

MCAGCC, 29 PALMS, CA (SCIMITAR – APR 97)

(Husain, Leheny, Mrksich, Wadley, Lytikainen, AMC/FAST (2), NSAP, UCLA/RSC (4) (1 Mar Div)







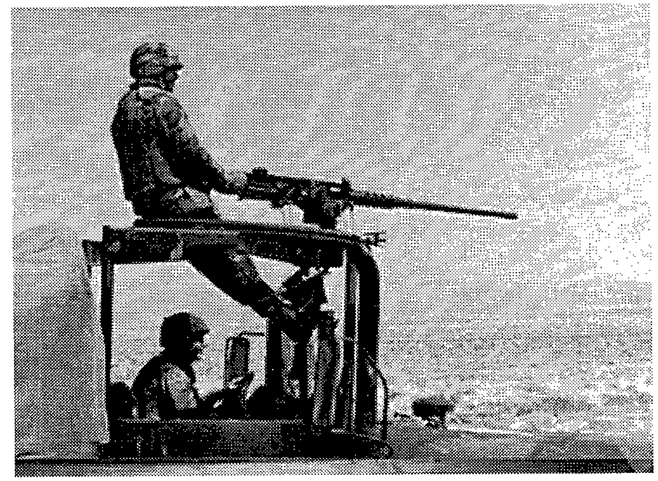
DARPA/DSRC Enjoying The Many Delights Of MREs

808-6-27-97-4

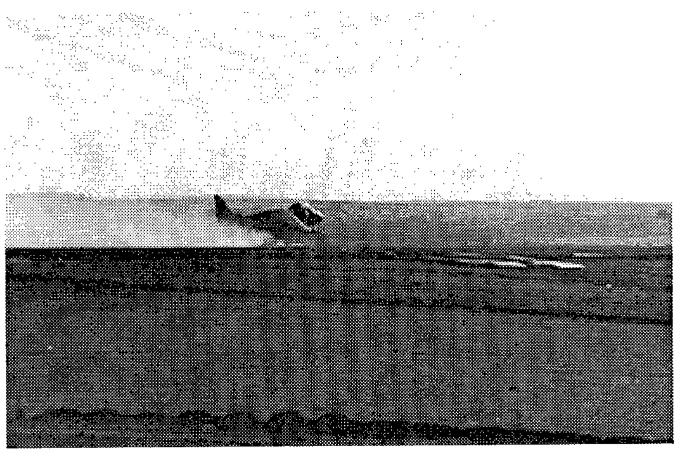
MCAGCC, 29 PALMS, CA (SCIMITAR – APR 97)

(Husain, Leheny, Mrksich, Wadley, Lytikainen, AMC/FAST (2), NSAP, UCLA/RSC (4) (1 Mar Div)

MGen Admire And Scientists



Gunner (50 Cal Machine Gun)



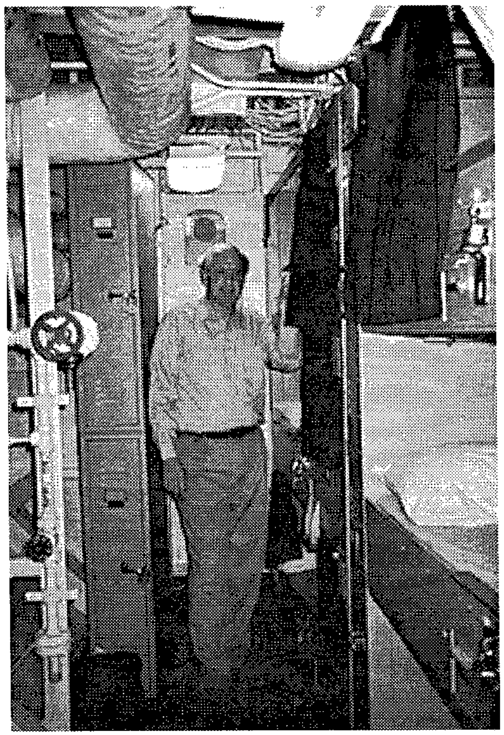
AV-8B Harrier

Spoils Of Victory

808-6-27-97-6

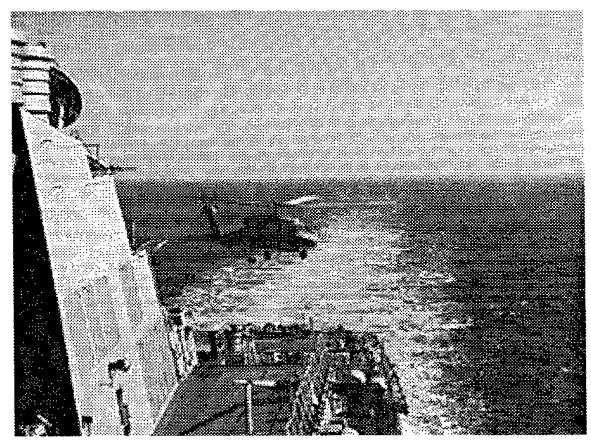
USS STETHEM (DDG 63) (AEGIS) (MAR 97)

(DSRC–Ferry, Lytikainen, NRAD–Gill, Rogers) (COMDESRON 21 Exercise)



19” Racks – Not Only For Electronics

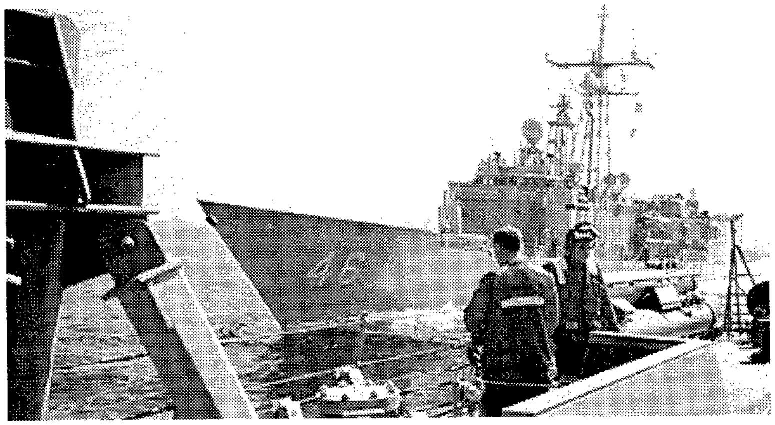
Helo OPS – Fire Fighting Crew



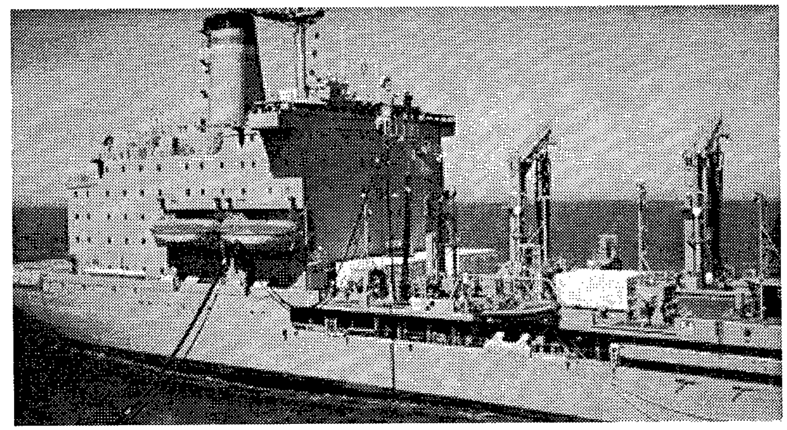
H-60 (LAMPS) Over Fantail

808-6-27-97-12

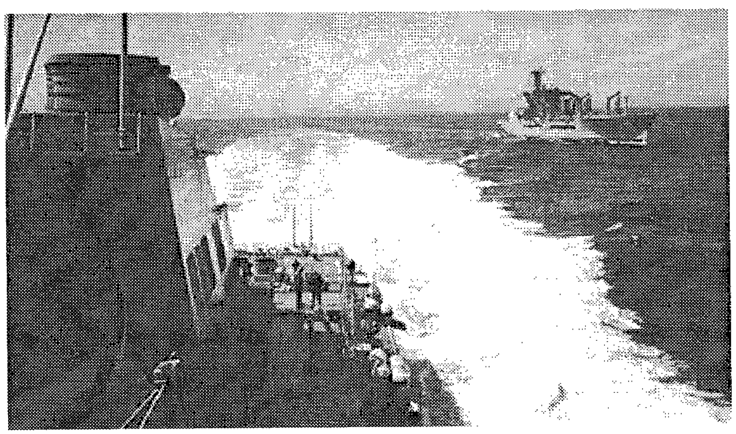
USS STETHEM (DDG 63) (AEGIS) (MAR 97)
(DSRC–Ferry, Lytikainen, NRAD–Gill, Rogers) (COMDESRON 21 Exercise)



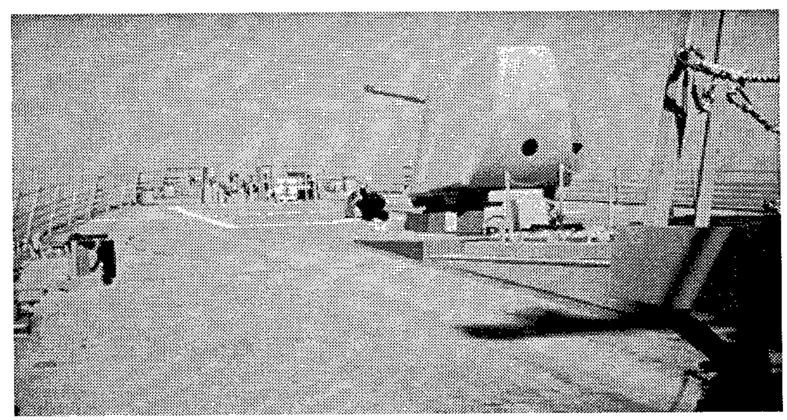
USS Rentz (FFG46)–
DESRON 21 Sister Ship



UNREP–USNS Rappahannock



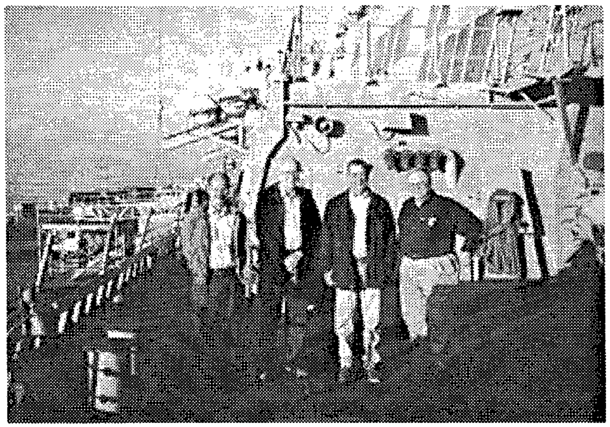
Emergency Break-Away Exercise



5” Gun

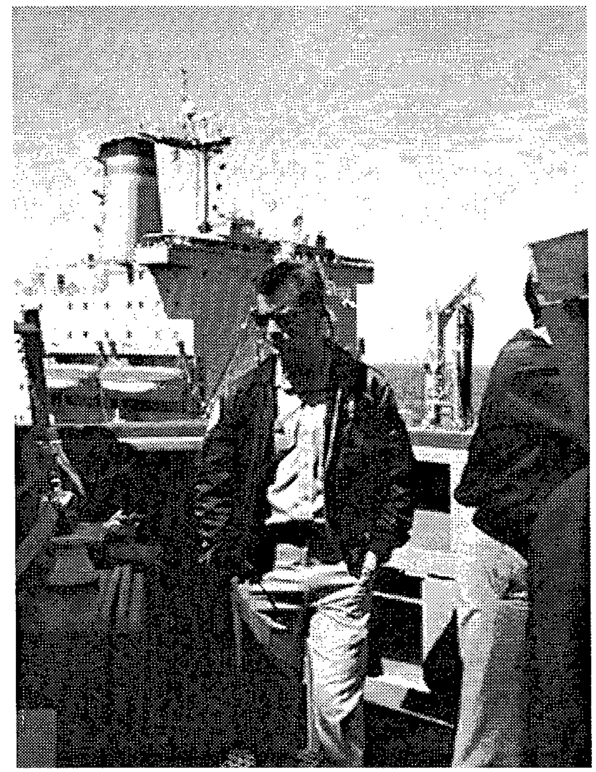
808-6-27-97-13

USS STETHEM (DDG 63) (AEGIS) (MAR 97)
(DSRC–Ferry, Lytikainen, NRAD–Gill, Rogers) (COMDESRON 21 Exercise)



Rogers, Ferry, Gill, Lytikainen

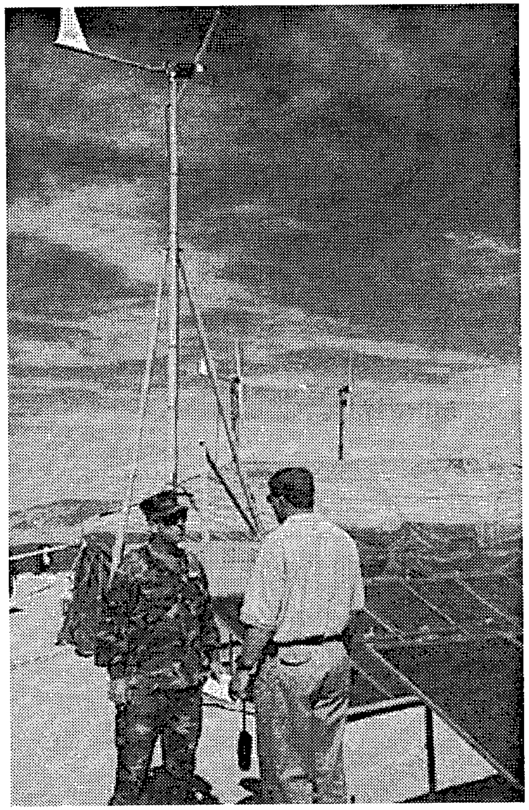
On Small Boat, With Stethem
Riding Off Into The Sunset

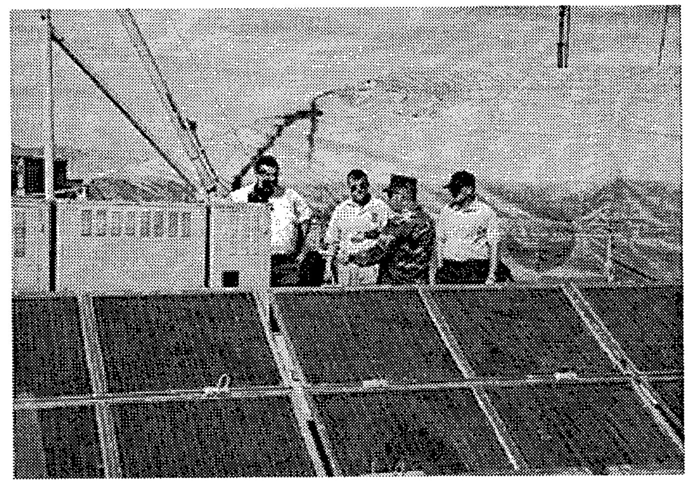


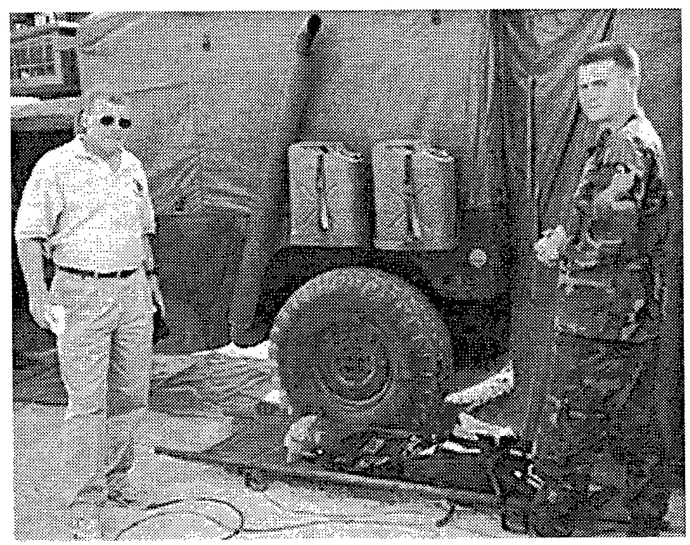
Commanding Officer–CDR Steve Miller

808-6-27-97-14

MCAGCC, 29 PALMS, CA
(HUNTER WARRIOR/AWE – MAR 97)
(Lytikainen, NSAP – Kiers, Francis, Ledigh) (CWL, 7th Marines)







Harvesting Energy
(Wind,Solar) And
MEDEVAC Technologies

808-6-27-97-7

U.S. NAVY USS CONSTELLATION (CV 64) (JAN 97)

(DARPA – Harr, CNAP/PAO DVs) (At-Sea, SOCAL OPAREA)

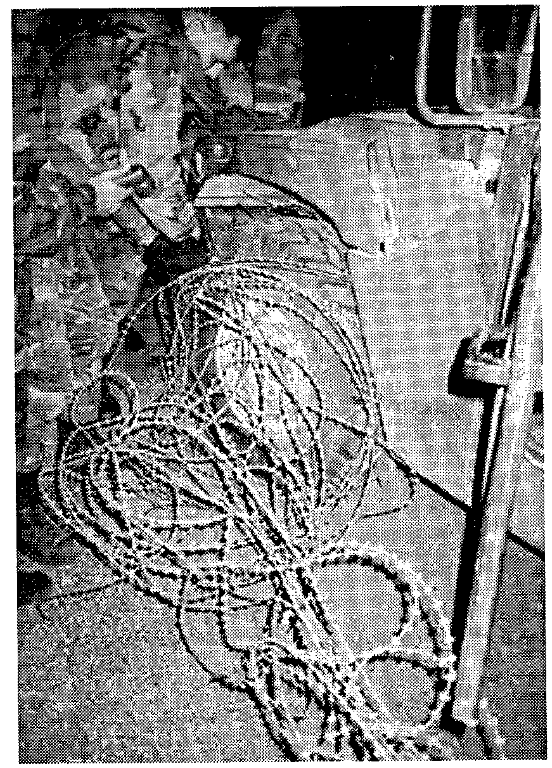
Strapping On Mae West

Heading For The C2

F/A-18s, S-3s, EA-6Bs On Deck

808-6-27-97-25

MCAGCC, 29 PALMS, CA (STEEL KNIGHT – DEC 96)
(E. Brown, Heuer, Kovacs, Lytikainen, Francis, Heilman, Kiers, Kaiser)
(7th Marines)



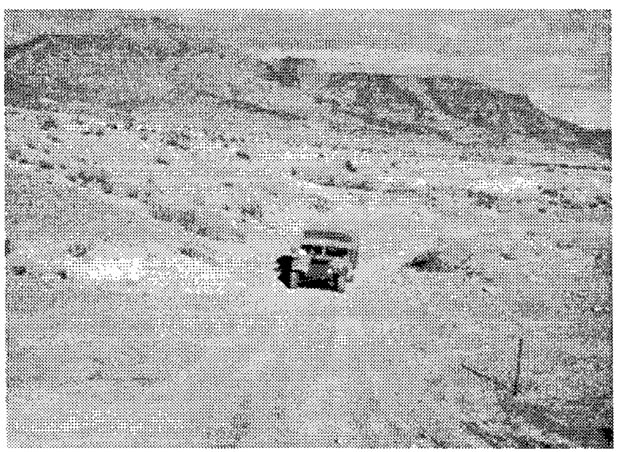
Night Patrol Encounter With Concertina Wire
– The HMMVEE Lost!

808-6-27-97-10

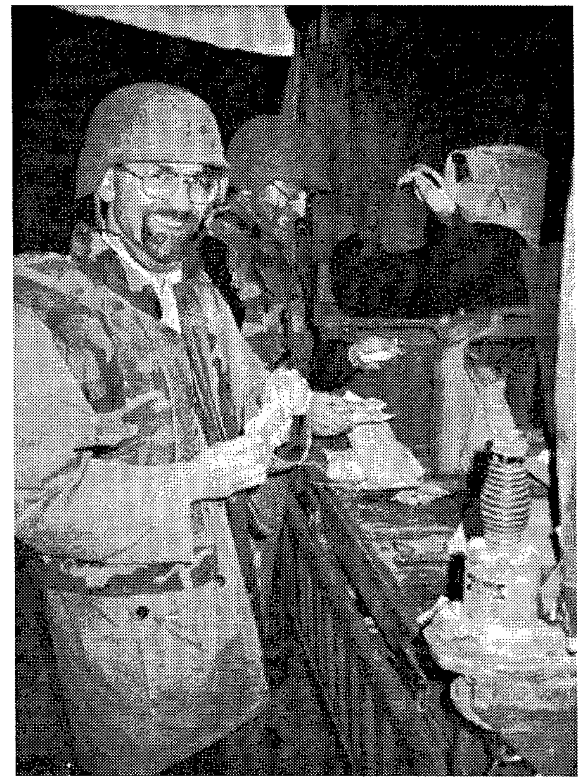
MCAGCC, 29 PALMS, CA (STEEL KNIGHT – DEC 96)

(E. Brown, Heuer, Kovacs, Lytikainen, Francis, Heilman, Kiers, Kaiser)
(7th Marines)

Hurry Up And Wait



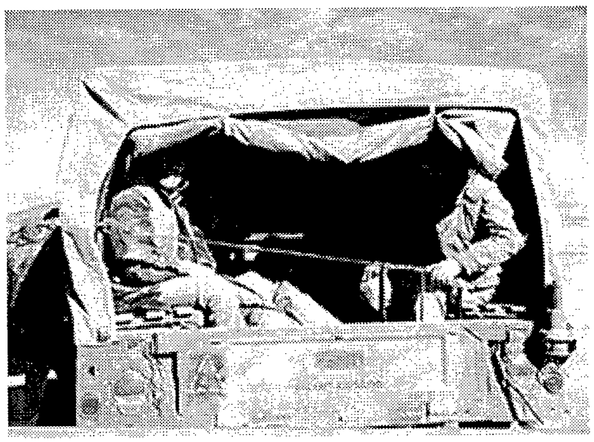
Heading For The Front



Cold Weather MREs – Run Over With HMMVEE And Add H_2O

808-6-27-97-9

MCAGCC, 29 PALMS, CA
(STEEL KNIGHT – DEC 96)
(E. Brown, Heuer, Kovacs, Lytikainen, Francis, Heilman, Kiers, Kaiser)
(7th Marines)



Dusty Warriors

M1A1 Tank Assault

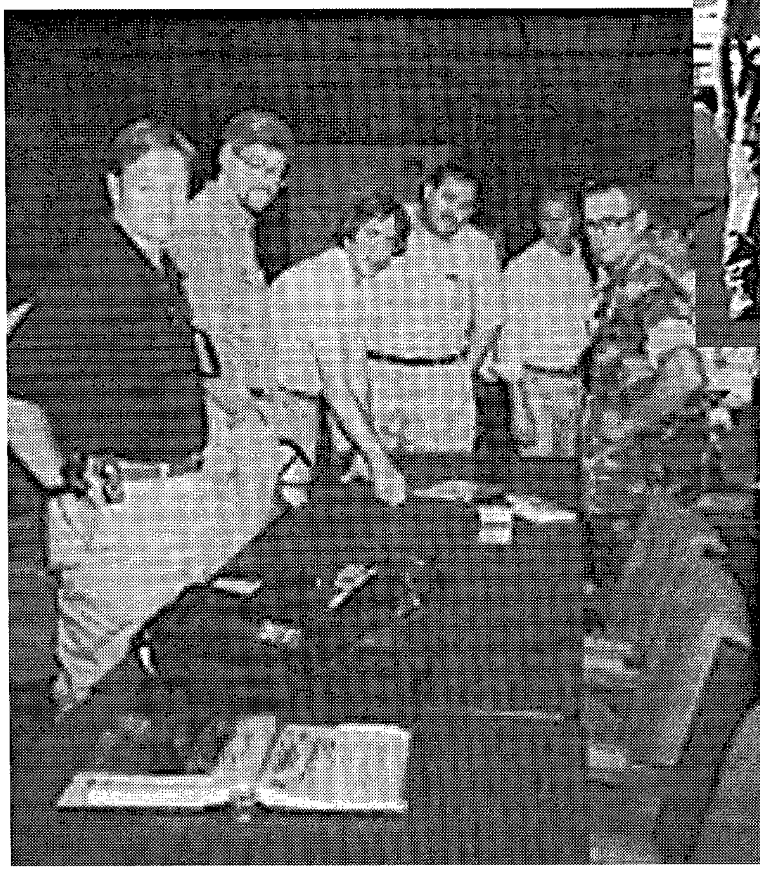
Victory Cigar

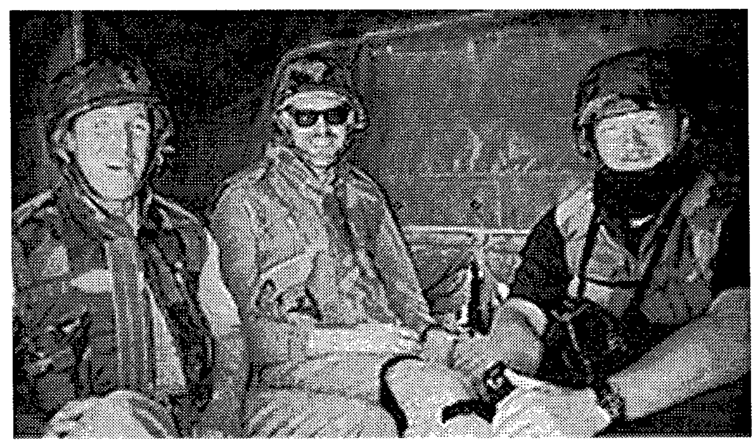
Weary Warriors

808-6-27-97-11

MCAGCC, 29 PALMS, CA (DESFIREX – SEP 96)
(Harr, Nowak, Pazik, Bales, Kiers, Lytikainen, CIA, UMICH, UCLA, Rockwell)


Pre-Insert Assemblage


LWIM Concept Demo

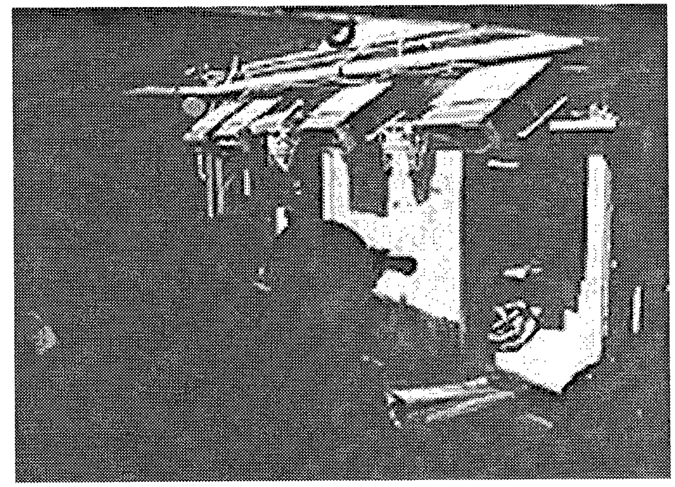

Enjoying The HMMVEE Ride

808-6-27-97-1

MCAGCC, 29 PALMS, CA (DESFIREX – SEP 96)

(Harr, Nowak, Pazik, Bales, Kiers, Lytikainen, CIA, UMICH, UCLA, Rockwell)

AAV Command Post



Inside AAV CP

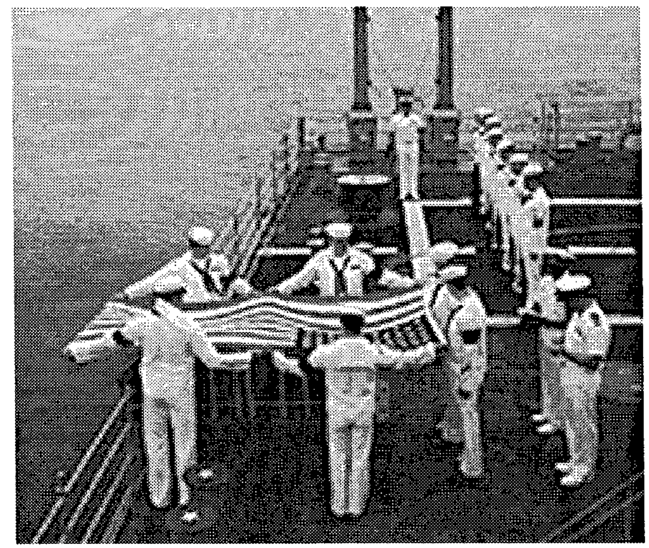
Warrior Harr

808-6-27-97-2

U.S. NAVY USS VALLEY FORGE (CG 50) (JUN 95)

(DARPA – Harr, DSRC – McGill, Lytikainen) (At-Sea, SOCAL OPAREA)

DSRC Master Cooks

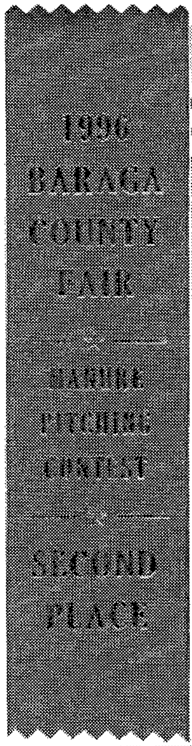


Burial At Sea

808-6-27-97-27

Pelkie, MI (Aug 96)

DSRC/DARPA Summer Training Camp — Manure Pitching

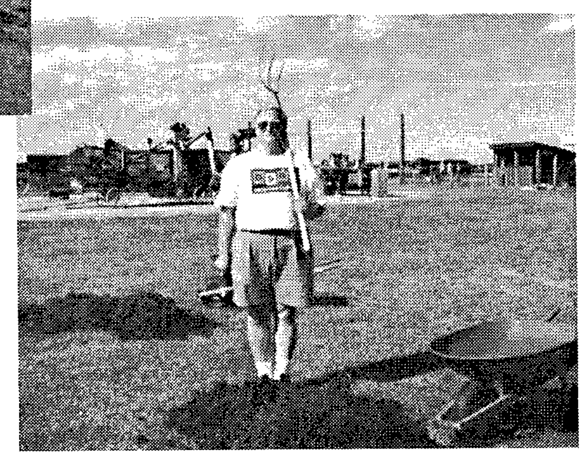


The Daunting Task

Loading 'er Up

Moving 'er Out
(200' dash)

Explaining Winning Technique



Ready to Brief the General

July 1997

31 July 1997

DSRC SUMMER CONFERENCE MILITARY VISIT SCHEDULE

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
13	14	15 1300-1600 **CENTCOM** AOR, Technical Challenges Earl Rubright Torrey Pines	16	17	18 ***FULL MOON (19th)*** *NO GRUNION HUNT In 1997!*	19 0900-1500 **COMTHIRDFLT** **USS Coronado** At-Sea In SOCAL OPAREA **JTFEX**
20	21	22	23 0900-1200 **CGIMEF** Amphibious Assault - "Red Beach", Camp Pendleton **JTFEX**	24 1230-1500 **Fleet Mammals** NRAD Point Loma	25	26
27	28	29	30	31 **WRAP UP**		

CENTCOM

July 15, 1997

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